Systems Design Report

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Executive Summary

Warwick Mobile Robotics (WMR) designed and built an Urban Search and Rescue (USAR) Robot prototype, developing the 2008 chassis and software and competing at the RoboCup German Open 2009. WMR accomplished its goal of producing a highly mobile robot that could cover all terrain though work is still required to make performance reliable and to optimise operation from a remote location.

Robot design is inherently a multi-disciplinary process so systems design techniques ensure that the various elements are compliant and unforeseen conflicts are minimised. This technical report follows the systems design procedure based on a systems V-diagram, identifying necessary capabilities of mobility over terrain, autonomous navigation, victim identification and manipulation. Functional requirements are specified from these capabilities to give performance criteria to provide a design basis and to provide evaluation targets during testing.

The competition provides a standard testing platform for measuring performance improvements of the WMR robot. Mobility requirements were met and autonomous operation was implemented. Victim identification is possible by a human operator but automatic detection is still in its infancy. Manipulation is an important feature to be explored in the future. A further benefit of the competition is to provide the group with a means of testing the robot's abilities with respect to other research groups investigating USAR robots. The WMR robot achieved third place in the 2009 German Open with a Best in Class award for Mobility, this has led to an opportunity to enter the World Finals in Graz, Austria.

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Figures, Tables and Equations

1 Introduction

This systems design report documents the Warwick Mobile Robotics (WMR) group project for the 2008/09 academic year. The project focused on developing an Urban Search and Rescue (USAR) robot for entry into the 2009 RoboCup Rescue competition.

Background to the project, as well as technical details of the work done and the results achieved, are given in this report. Details of support activities conducted as part of the project are given in the Business, Finance, Publicity and Management Report.

The project aim is the development a USAR (Urban Search And Rescue) robot for entry into the RoboCup Rescue competition. The WMR entry at the 2008 German Open is being developed.

1.1 Background to Autonomous Robotics

Autonomous robots are robots able to operate without constant human guidance. Different robots may exhibit different levels of automation, for example factory robots operating autonomously within the confines of a relatively well known environment exhibit a low level of automation. Robots able to operate in unstructured and unknown environments exhibit much higher levels of automation.

In order to exhibit full autonomy a robot must be able to:

- Gain information about the environment
- Work for an extended period without human intervention
- Move either all or part of itself throughout its operating environment without human assistance.
- Avoid situations that are harmful to people, property, or itself unless those are part of its design specifications.

Achieving these aims requires the interaction of multiple subsystems – these will vary from robot to robot, however there are some features common to almost all autonomous robots. Section 2 provides an introduction to some of these features.

1.2 Features of Autonomous Robots

1.2.1 Sensors

Sensors are used by autonomous robots to gain information about their environment and themselves, this is crucial if a robot is to operate without human intervention. Even a relatively simple robot, such as the Roomba (a vacuum cleaning robot discussed in Section 0) must be able to detect collisions to be of any use. Internal sensors include encoders used to measure wheel rotation, heat sensors for onboard electronics and battery charge sensors. External sensors are very varied and depend on the application. Common examples include proximity sensing (for example Light Detection and Ranging (LiDAR) or ultrasound), auditory sensing and vision.

1.2.2 Mapping

In order to move intelligently through an environment, an autonomous robot must be able to locate its self in the environment and remember the locations of relevant objects – in other words it must be capable of Simultaneous Localisation and Mapping (SLAM). SLAM has attracted much research attention due to the inherent weakness in mapping or localising independently: as a robot moves, sensor errors will lead to incorrect estimation of robot position and in the estimation of object locations. In creating a map a robot will use its estimated positions to place the objects it senses, thus errors in position estimation will have a systematic effect on map errors, or: "error in the robot's path correlates errors in the map" (1). Various statistical techniques are employed to implement SLAM including Kalman filters and particle filters and it is now generally considered a prerequisite for true autonomous operation.

1.2.3 Decision Making and Autonomy

To provide a useful function, autonomous robots must use sensory data to generate commands to actuators. The kind of decision making required is entirely application specific and ranges from simple collision avoidance algorithms to highly complex strategic decision making such as that exhibited by robot football teams. Different approaches may be used for decision making depending on the application, these include procedural "IF * THEN *" statements and more complex artificially intelligent approaches such as neuro-fuzzy systems. More complex strategies may incorporate machine learning – using past experience as an input to the decision making process.

1.2.4 Example Applications

1.2.4.1 Research

Stanley is a robot developed by a team of researchers at Stanford University's Stanford Racing Team in cooperation with the Volkswagen Electronics Research Laboratory (ERL) which won the 2005 DARPA Grand Challenge. The robot is a Volkswagen Touareg modified for autonomous driving. Software was written for the robot to feed "data from LIDAR, the camera, GPS sets and inertial sensors into software programs [to control] the vehicle's speed, direction and decision making" (2). Sensors used include five LiDAR units used to create a 3D map of the environment, a GPS positioning system and gyroscopes and accelerometers used to monitor the orientation of the vehicle.

Figure 1-1: Darpa race winner Stanley(2)

1.2.4.2 Commercial

The Roomba is a robotic vacuum cleaner developed by iRobot, and one of the first commercial autonomous robotics systems.

Figure 1-2: iRobots Roomba vacuum cleaner (3)

This robot exhibits a high level of automation, for example the Roomba will locate and return to a docking station to recharge when the battery is low and drop offs are detected using infrared sensors. Sensors include a contact sensor on the front of the robot to detect collisions, infrared sensor to detect docking stations. Additionally the Roomba senses the level of dirt passing through its brushes and modifies its cleaning pattern accordingly. This robot does not map its environment; instead it uses simple algorithms to increase efficient area coverage.

1.3 RoboCup Rescue

RoboCup Rescue is a competition aimed at fostering the development of robots for urban search and rescue applications. Specifically, the competition aims to:

"Increase awareness of the challenges involved in search and rescue applications, provide objective evaluation of robotic implementations in representative environments, and promote collaboration between researchers." (4)

The competition is based on a simulated disaster area; robots must negotiate, and produce a map of, the terrain in this environment. Points are awarded for locating simulated victims and placing the locations of these victims on the map of the terrain. The competition has several regional open (including the European German Open) competitions and an invitation World Final. It is part of the larger RoboCup which incorporates robot football, rescue and home robotics.

The competition terrain consists of three areas of increasing difficulty, each containing simulated victims:

- Yellow arena: consists of a maze like structure with sloping floors. Within this arena the robot must operate autonomously.
- Orange arena: as above with the addition of step-fields and confined areas under low ceilings. Within this arena the robot is tele-operated.
- Red arena: as above with the addition of stairs, ramps and more challenging step fields.

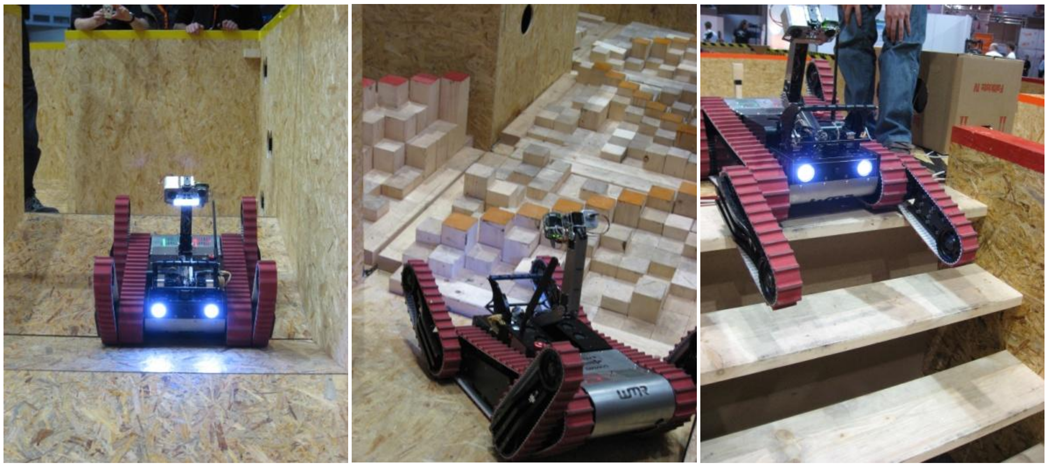


Figure 1-3: (Left to right) yellow ramps, orange step field, red staircase

The purpose of the competition is to locate simulated victims – these emit the following signs of life:

- Form: dolls or mannequin arms are used to represent victims
- Movement: arms may be waving
- Sound: Dictaphone used to emit human sounds in the form of a repeating list of sets of similar sounding words that must be identified
- Heat: electric heaters are used to simulate body heat
- CO_2: entrapped victims emit CO_2 causing a build-up of at least 2000 parts per million

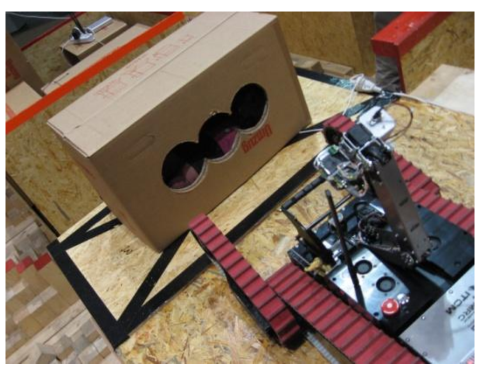


Figure 1-4: Trapped victim

The competition rules are found in Appendix C.

1.3.1 Development for the 2008 Competition

This project represents the second year for which WMR has been involved in the development of a search and rescue robot. During the 2007/08 academic year, the WMR project team developed such a robot from scratch and entered it into the 2008 RoboCup Rescue competition. The robot was able to medium difficulty obstacles (orange step fields and ramps) and featured the sensory capabilities to locate victims (form and thermal). A full analysis of this robot's performance is given in Section 0.

The robot was tele-operated from a remote computer with no artificial intelligence and could not tackle the red stepfields and staircase. These challenges are the primary motivators for further development to better meet the competition requirements and demonstrate the technology available to search and rescue markets.

Figure 1-5: 2008 robot on a stepfield

1.3.2 Further Development Aims for the 2009 Competition

For 2009, WMR will continue to focus on search and rescue robotics, using the robot entered into the 2008 competition as a starting point. Analysis of the performance of this robot will be used to identify areas for improvement and guide the selection of particular technologies and solutions.

The aims and objectives for this project are as follows:

- Build on the success of 2008
    - Optimise tele-operation
    - Implement mapping and autonomy
    - Investigate further victim identification
    - Achieve Best in Class for Mobility at RoboCup Rescue German Open
    - Qualify for the international final in Austria
- Raise the profile of WMR and sponsors through continually developing marketing strategy
- Increase awareness of Engineering both at the University of Warwick and as a profession
- Showcase Warwick innovation to the world

1.4 Design Methodology

A systems perspective is used for all design work in this project.

The 2007/8 project was split into two parallel streams: hardware and software. While there was communication between the two areas they were treated as separate, for example requirements were separated into hardware and software. This approach leads to "technology owners" – individuals or small teams focused on delivering a particular technology.

This project involves developing and improving an existing design and as such focuses on capabilities, such as sensory capabilities, rather than technologies. The capabilities of a robotics system are generally determined by the interaction of multiple subsystems covering different technologies and engineering disciplines. This approach leads to WMR being "capability owners" with small cross-disciplinary teams working together.

There are three high level stages to a systems engineering design project as shown in Figure 1-6. The systems design phase begins with an analysis of the capabilities of the system as a whole before feeding down into subsystem specification. Similarly, the systems verification phase first tests individual components before ensuring the whole systems meets the system specification. Such an approach, when followed properly, ensures that all subsystems interact to deliver the required overall performance.

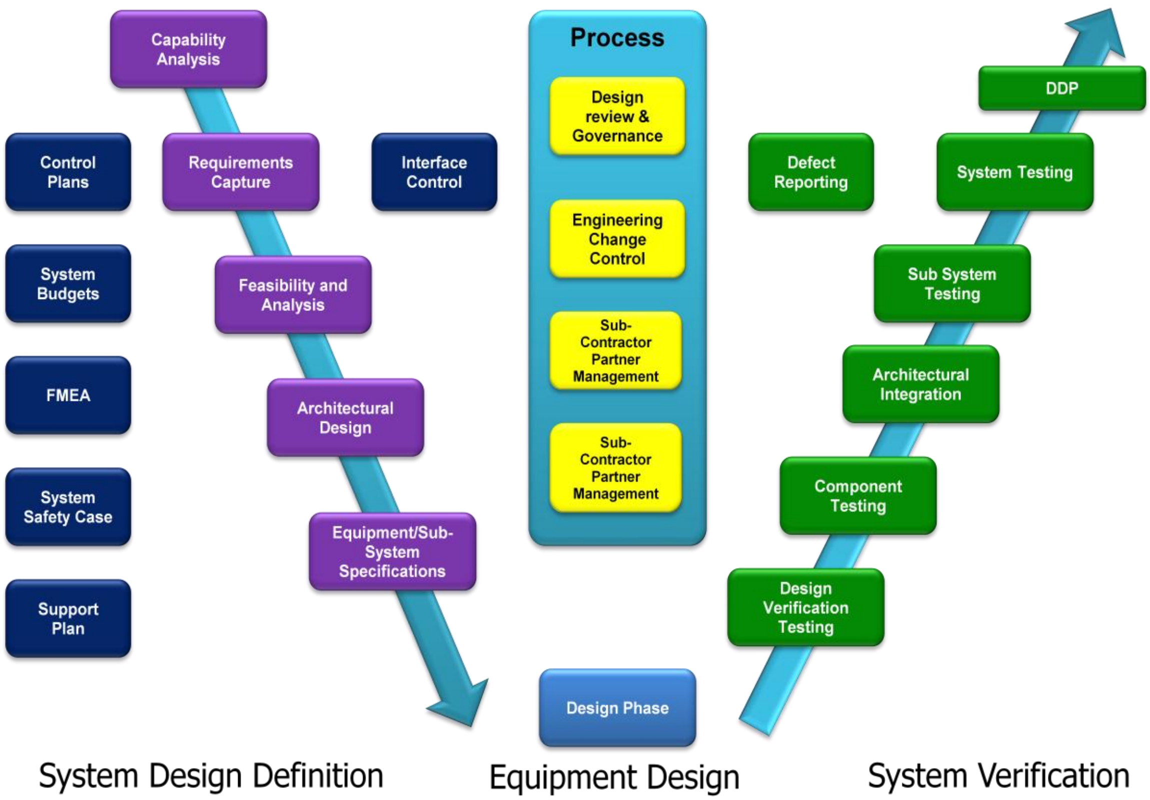


Figure 1-6: Systems V-Diagram (Northrop Grumman Remotec)

Specific tools were utilised for the design process and the design procedures and details of the design procedures follow.

1.4.1 System Modelling Methods

When modelling and documenting the robot system, it was important to use a standardised toolset, to ensure accuracy and continuity. SysML(5) was identified as the perfect tool to model a complex system such as ours which contains interdependent hardware and software elements. These models were then used extensively during the analysis and design stages of the project, to enable complete visualisation of the system.

1.4.2 Software Design Methods

The Agile software development philosophy is utilised in this project. Such an approach is appropriate in light of both the limited project time and shifting specifications as a result of hardware changes, budgetary changes or unforeseen circumstances. Within this framework certain tools are used to support the development process. It also reflects the dynamic nature of the software tasks and team composition.

Unified Modelling Language (UML) is used to describe the functionality of software constructs from entire capabilities such as autonomous navigation, down to individual functions. This provides an unambiguous language in which to describe and share designs within a team.

Subversion, the version control software, is used to track changes to source code and maintain a central library of current and historical versions of files. This allows multiple users working on different machines to view, run and edit the same Java project. The Subversion server is hosted by Warwick Computer Science Society.

Continuing from the 2008 robot, Java is used for all robot and base station (client) software. Java programs are not precompiled for specific operating systems so the programs can run both on Windows machines for development and for the client, and on a Linux machine when deployed on the robot.

1.4.2.1 Atmel Microcontroller Programs

Atmel AVR controllers have previously been used by WMR for robot football and robot rescue. Programs are written in C using the free proprietary AVR Studio program using standard libraries and added to the Subversion server.

1.4.3 Hardware Design Methods

1.4.3.1 The SolidWorks Design Process

Any three dimensional (3D) parts files shall be created within SolidWorks 2008, Service Pack 2.1. These parts shall be saved in the relevant file directory conforming to the system below.

The directory structure for designs, in the network drive Mechanical Design folder, is as follows:

Design Year → Parts Group → Parts Subgroup → Part inc. Rev
→Superseded →parts inc. Rev

The parts created shall be suitable for manufacture using in house facilities which include 5 axis milling machine tools and CNC lathes. Specific attention will be paid to all part features which may create difficult manufacturing conditions.

Most parts to be manufactured shall be saved in '.STEP' format, excepting those for laser cutting/folding which will be in '.dxf' format. Files which are to be used for manufacturing shall be saved in the .STEP (AP214) format, which is compatible with the relevant machine tool programming software.

A standard drawing shall be completed with (as a minimum):

- Overall part dimensions
- Depths and dimensions of all holes, counterbores and cuts
- Finish of all holes, thread size if tapped, bore if clearance. The thread pitch is not necessary as standard pitches shall be adopted for all equal sized bolts where possible. Metric (M) bolts shall be used throughout the chassis for mechanical fastening.
- Quantity of parts required
- Material of manufacture
- Finish to be applied (i.e. powder-coating, as machined, hard anodised)
- The part manufacturing code comprising of a letter (M – Machining, T – Turned, B – Folding sheet) and part number as shown in Appendix A
- Drawing/part revision number.

The drawings shall be completed on the WMR sheet design built as a SolidWorks template.

A works request in Appendix E shall be completed for each and every part stating the material of manufacture, quantity and any special manufacturing details relevant to the manufacture of that part.

1.4.3.2 Altium DXP Design Process

Design of electronic circuits was performed with the Altium DXP 2004 package. This incorporates schematic capture, for circuit diagram drawing, and PCB layout. With built in design rule checking (e.g. track width, short circuit, un-routed, etc.) it provides a robust design tool.

Template pages were designed to hold all WMR schematics and carry the file location, author, date of creation and circuit name.

A standard naming convention was adopted as in Table 1-1. This will make referencing designs easier in the future, although only one circuit board was designed for the 2009 robot.

A change to the PCB copper layout, after manufacturing a board, results in a new Revision. The old files should be retained as the previous Revision.

A change to a schematic with no new layout (e.g. a component value change) creates a new Issue to differentiate boards with the same layout but different parts. Each populated PCB will be marked with the Issue number so that it is known which component set is present.

Table 1-1: Naming convention for electronic design files

File type	
Project	0809_Name_RevX.PrjPCB year_name_revision
Schematics	0809_Name_RevX_SCH_xxx_xx.SCHDOC year_name_revision_SCH_uniqueNumber_issueNumber.SCHDOC
PCB	0809_Name_RevX_PCB_xxx_xx.PCBDOC year_name_revision_PCB_uniqueNumber_issueNumber.PCBDOC

The directory structure for designs, in the network drive Electronic Design folder, is as follows:

Board name folder → Folder for each Revision

e.g.

Power Board → 0809_PowerControl_RevA

1.4.3.3 National Instruments Multisim

Multisim was used for circuit development and simulation when constructing a real proto

2 Requirements Analysis

2.1 Stakeholder Analysis

Before defining the requirements for this project time was spent considering all possible WMR stakeholders with respect to their interests in the project development and outcome.

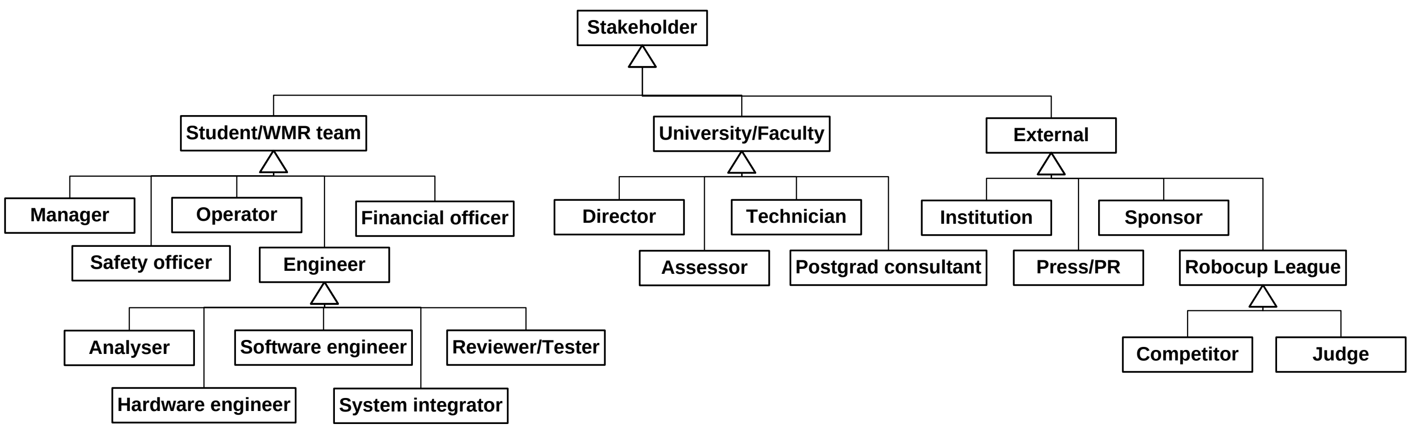


Figure 2-1: Stakeholder diagram

The project is targeted at the external RoboCup so the development aims of the competition must be considered, but sponsors are seeking exposure. The University also seeks exposure but like the WMR members also intends to promote personal development.

2.2 Capability Analysis

The following chapter describes the capabilities the robot should posses in order to achieve the team's stated aim of success at the European leg of the RoboCup Rescue competition. Certain capabilities reflect the challenges posed by the competition as well as the manner in which the competition is judged (Appendix C for competition rules). Other capabilities reflect basic principles of any engineering project such as testability and safety.

2.2.1 Mobility

Simulated victims are located throughout the competition terrain thus the robot should be mobile over all areas of the terrain. The more challenging aspects of the terrain include a 45° ramp, stair sets and "red" step fields and a maximum step height change of 30cm (Section 0 and Appendix C for arena specifications).

The robot shall be intuitively operated with no uneven track control over the entire operating time of the robot. This means that uneven track tensioning or varying motor performance levels shall not cause different speeds on each side of the vehicle for equal control signals.

2.2.2 Power Systems

The robot should, without any external wired connection, provide power to all onboard equipment at the correct voltage and current. The competition consists of several periods where the robot has a maximum of 25 minutes to negotiate the terrain and locate victims. The capacity of the power system should therefore be sufficient for at least this length of time.

The robot will also be used for demonstration and publicity purposes to promote the work of the University of Warwick and find further applications for autonomous vehicles. The expected duration of these activates must be considered in setting the capacity requirements of the power system.

Remote power cycling of all devices is desirable. This allows individual subsystems to be shut down when not required and reset should a software fault occur, saving energy and reducing the risk of systems locking up. People's lives could depend on a search and rescue robot finding them and this should not be jeopardised by the loss of any detection system.

2.2.3 Victim Identification

An urban search and rescue robot must detect people trapped in collapsed buildings, possibly under rubble. Humans emit several signs of life and the RoboCup Rescue victims are similar.

- Form
- Movement
- Heat
- Sound
- CO_2

Not all signs may be observable so the USAR robot should detect as many signs of life as possible. For example victims may be entombed within a structure and thus difficult to see, but possible to detect through a build-up of CO_2. There may also be hazards around the victims such as gas canisters or chemicals so it is important the robot can relay information back to the operator about the victim's situation. Due to the varying situations of the victims most sensors should be on a flexible platform that can be positioned for optimum observation.

The readings from victim identification should be returned to the operator to make any final decisions on stability and risk to the individual.

2.2.4 Tele-Operation

The robot must be capable of remote operation by a single operator. Since the terrain is unknown wireless communication is needed since wires could be caught on or loop around obstacles.

2.2.5 Autonomy

The competition terrain is split into three areas of increasing difficulty: "yellow", "orange" and "red". While in the yellow area the robot must navigate autonomously while detecting victims. This involves collision avoidance and autonomous victim identification.

From the RoboCup rules

- No human intervention other than to confirm victims
- Operator takes control at any point

In real applications, research (Rapid UK[1]) has indicated that rescue teams would be unlikely to use autonomous mobility functions but that victim identification could be useful to detect anyone visually obscured. Also, should the robot lose communication with the base station it could use its autonomous capability to return to a point that had good communication.

2.2.6 Mapping

The robot should produce a map of the environment it passes through and add victim locations as they are discovered. The format of the map should correspond to the GeoTIFF standard for embedding geo-referencing information within a TIFF file.

In a real rescue application this map is essential for rescue workers to enter the area and extract the victims. It also allows the robot to track its position and path and fully clear and area before moving on, and not retrace its steps unless necessary.

2.2.7 Manipulation

It is advantageous for a rescue robot to deliver items to trapped people such as emergency food or a two-way radio. Pick and place functionality is necessary for this.

2.2.8 Testing & Development

A robotic system is composed of various sub-systems, including sensors, processors and actuators. The integration of these sub-systems must be such that each one can be operated and tested independently of the others. In practice this requires a modular design and a clear understanding of the relationships and information transfer between sub-systems.

Additionally, appropriate tools should be provided for the testing and verification of all sub-systems.

[1] Rapid UK – Rescue and Preparedness in Disasters (http://www.rapiduknews.org.uk 28/4/2009)

Man-machine interaction is an essential part of any engineering project. The ability to operate the robot effectively on the course terrain it will face in competition is vital.

2.2.9 Safety

Normal operation of the robot must not pose a danger to property or life. Provisions must be made for a failsafe stop function in the event of abnormal behaviour and the remote (operator) and local (on the robot) emergency stop is needed.

2.3 Initial State

The robot developed for the 2008 competition provides a logical starting point for the project. This section describes the performance of the robot at the outset of the project in relation to the capabilities described above.

2.3.1 Mobility

The 2008 robot was highly mobile over the majority of the terrain, including the 45° ramp. The robot was unable, however, to negotiate "red" step fields or ascend stair sets. The major problems in overcoming these obstacles are detailed below:

- The centre of mass (CoM) of the robot is not sufficiently far forwards, leading to toppling at climb angles over 50° degrees from the horizontal. The CoM is a function of the manufactured chassis and purchased components weight and locations within the completed robot.
- Flipper belt stripping. The bonded layers of the flipper drive belts were prone to shearing when the robot attempted to lift its own weight, refer to Figure 2-2.

Figure 2-2: Typical flipper drive belt failure

- Drive track slipping. The drive tracks rely on their coefficient of friction to provide a gripping surface for drive. After continuous use the high friction surface layer becomes worn and dulled. No mechanical locking method for attaining grip is featured in the current track system.
- Reverse drive climbing. The pulleys outer diameter matches closely with the geometry of the rear of the chassis Figure 2-3, for this reason the robot cannot grip and climb vertical surfaces when travelling in reverse. Ascending stair sets could be achieved with current track system had the robot been able to climb in reverse (thus overcoming the CoM issue stated earlier).

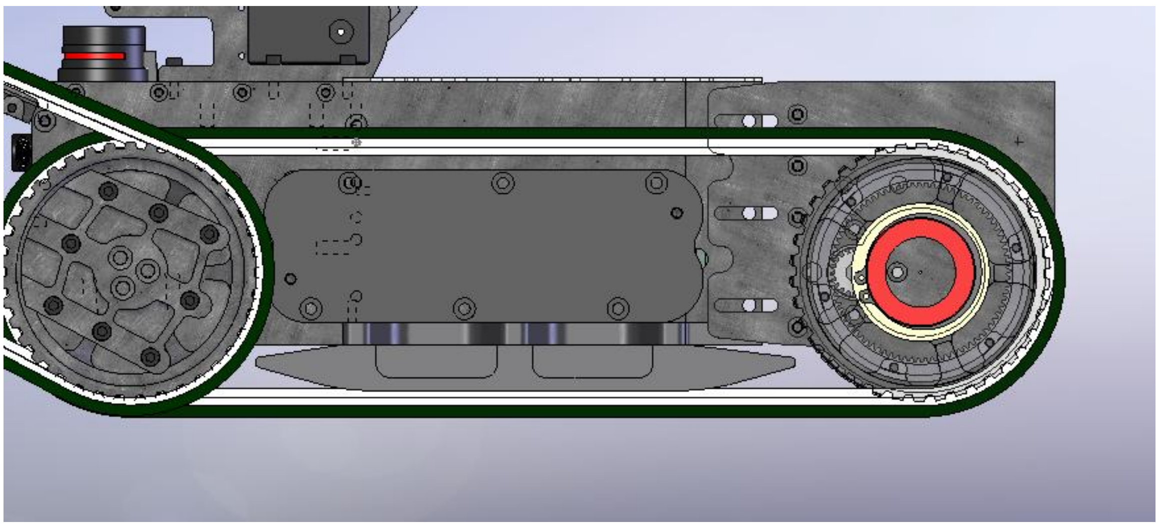


Figure 2-3: 2008 robot chassis rear geometry

The drive motors had no feedback so operated in an open-loop system. Optical encoders were fitted to the motors so closed-loop speed control could be implemented. Speed control will allow the control board to monitor the output of the motors and increase or reduce power as necessary to maintain this speed.

2.3.2 Power Systems

Two onboard batteries provided power to the robot whilst a power distribution board regulated supply to subsystems. Nickel-Metal-Hydride (NiMH) D-cells were used in custom designed packs to deliver 24 V. After a full charge, the robot's run time over representative competition terrain was 20 minutes, a decrease on the design run time due to use over the previous year. These batteries also dropped voltage when delivering high current, for example when the robot is tackling a ramp of staircase, which could cause other systems to drop-out.

The power board did not offer remote power cycling.

2.3.3 Victim Identification

The robot was equipped with the following sensors for victim identification:

- Two webcams (one forward and one rear facing)
- Infra Red (IR) camera – currently temperamental

The outputs of these sensors were transmitted to a remote user allowing victim identification through form, movement and heat. A microphone was present on the forward facing webcam but this information was not observable or recorded.

A robot arm exists carrying a webcam and IR camera. There was no control of this arm and it was fixed in place.

2.3.4 Tele-Operation

The 2008 robot was operated over a wireless network link using an onboard router as an access point and a wireless card or adapter on the client computer. The robot supports the IEEE 802.11 a, b and g network specifications. Communication between user terminal and robot was based on an object stream where Java classes are packaged and sent to the robot to be processed. This involves operations at both ends and can consume high bandwidth due to un-optimised data being transmitted.

2.3.5 Autonomy

No autonomy was implemented on the robot though LiDAR and sonar sensors were fitted to the chassis with the LiDAR readings sent back to the client and displayed.

2.3.6 Mapping

No mapping functionality was provided but crude maps could be drawn manually from inspection of the webcam outputs and LiDAR data.

2.3.7 Manipulation

No pick and place functionality existed.

2.3.8 Testing & Development

The 2008 robot featured some design and construction modularity which meant that several subsystems could be operated independently.

- USB controlled arm allowed independent operation
- Drive and flipper controllers operate over serial communication without other systems
- Webcams had Ethernet connections and send back pictures without the onboard computer
- IR camera has TV output allowing software development on other computers

The chassis provided by Remotec allowed software testing while the robot was dismantled. Sensors could be mounted to this development chassis.

2.3.9 Safety

A physical emergency stop button is fitted to the top of the robot that cuts the power to all moving parts. The robot design was for a “heart-beat” signal to be sent from the robot computer to a microcontroller on the power board that activates a soft E-stop if the heart-beat stops. This signal is sent while the robot computer is running the robot software and in communication with client software at the base station. The soft E-stop could be triggered manually. These functions were designed into software but had been disabled after a hardware failure in the safety controller. The hardware E-stop was operational.

These precautions would mean that the robot failed to the stop condition and it could be remotely and locally stopped.

2.4 Requirements Capture

Analysing the necessary capabilities for an urban search and rescue robot with respect to the functionality of the robot at the 2008 competition provides the basis of development for 2009.

2.4.1 Mobility

- To ensure mobility over the entire terrain, the robot shall.
- Ascend and descend, in forwards and reverse drive, a 45° ramp, with or without a carpeted surface.
- Ascend and descend, in forward and reverse drive, a standard size (riser and land) stair set consisting of no less than five steps with rounded or sharp edges.
- Negotiate all grades of stepfield as specified in competition rules Appendix C.
- Provide flipper control over 360° of rotation, with visual on screen display for operator information.

Alongside these mobility requirements, the robot shall demonstrate intelligence in protection for itself and its components from tipping and rolling.

The robot will be tested by driving over the specified obstacles and its success measured qualitatively from the point of view of the ease and closeness to tipping.

2.4.2 Power Systems

The robot power distribution system will provide the necessary power capabilities.

- The robot shall have minimum operating time of 25 minutes using onboard batteries when undertaking a rescue operation
- The robot mass should be kept low, and within 10 kg of the 2008 robot (which had mass of 36 kg)
- The robot should have remote power cycling of all electronic subsystems and be able to independently turn them off

And two hours when being run casually (e.g. for demonstration events)

The robot will be weighed on a set of scales, and individual components massed, to identify the sources of changes from the previous robot mass. During the competition the run-time can be evaluated.

2.4.3 Victim Identification

To ensure victim detection as fully as possible, the robot shall allow for the detection of the following signs of life and send this information back to a remote user:

- Form
- Movement
- Heat: detect the heat emitted by a human body in an indoor environment
- Sound
- CO_2: detect concentrations above 2000ppm

In addition, it must be possible to read any warning or hazard notices around the victims from 0.6 m away (half of one arena tile).

A moveable sensor platform (robot arm) shall be provided to get the sensors to the best position for observation. A protection system should be provided to move the arm to a safe location in the event of the robot tipping over. This will reduce the risk of damage to the expensive sensors.

During the competition the victim ID methods will be fully tested including use of the robot arm.

2.4.4 Tele-Operation

The robot shall be operated by a user who cannot view the robot, using only the sensor information relayed back to the user terminal. The robot shall be operated at range of up to 30 m from the base station.

2.4.5 Autonomy

Autonomous navigation is a requirement of the yellow competition arena.

- The robot shall navigate autonomously, avoiding collisions through a maze of grid squares of 1.2 m x 1.2 m.
- The robot shall autonomously locate victims using at least one sign-of life.

A competitive autonomy run will test these capabilities. Autonomy will also be tested prior to the competition using the WMR testing and demonstration arena. Software design is an iterative development process and ongoing AI evaluation will be performed.

2.4.6 Mapping

A map of the arena shall be produced indicating the victim locations and the current location of the robot.

The mapping quality is determined in the competition using a ground truth map. Maps produced by the robot will be compared to known, accurate layouts of the terrain in both simulation and real test runs.

2.4.7 Manipulation

The pick and place functionality has not been confirmed as part of the 2009 competition. Therefore no pick and place will be built into the robot though consideration will be given to future implementation.

2.4.8 Testing & Development

An arena representative of the competition terrain shall be constructed for testing and demonstration and shall contain examples of simulated victims.

To fully represent the competition arena a stair set, ramp and two customisable stepfields are required which will be to standard RoboCup specification (Appendix C).

Each subsystem shall be independently separable from the system (modular design) whole to allow testing of individual components.

A simulator shall be provided for fast development of software features (mapping and autonomy) by producing sensor data.

2.4.9 Safety

The robot shall have an emergency stop on the robot that physically cuts power to the motors. There shall also be the ability to stop the robot remotely from the base station. This software emergency stop shall also be triggered when communication or the onboard computer fails.

A Failure Modes and Effects Analysis is provided in Appendix D (FMEA) identifies possible faults and their effects, and how to manage them. Manually triggering the non-catastrophic conditions ensures that the robot failure is as expected.

3 Architectural Design

The robot architectural design refers to the process of identifying the subsystems that will make up the robot. After subsystems have been identified the subsystem requirements can be developed to meet the overall system requirements.

3.1 Systems Architecture

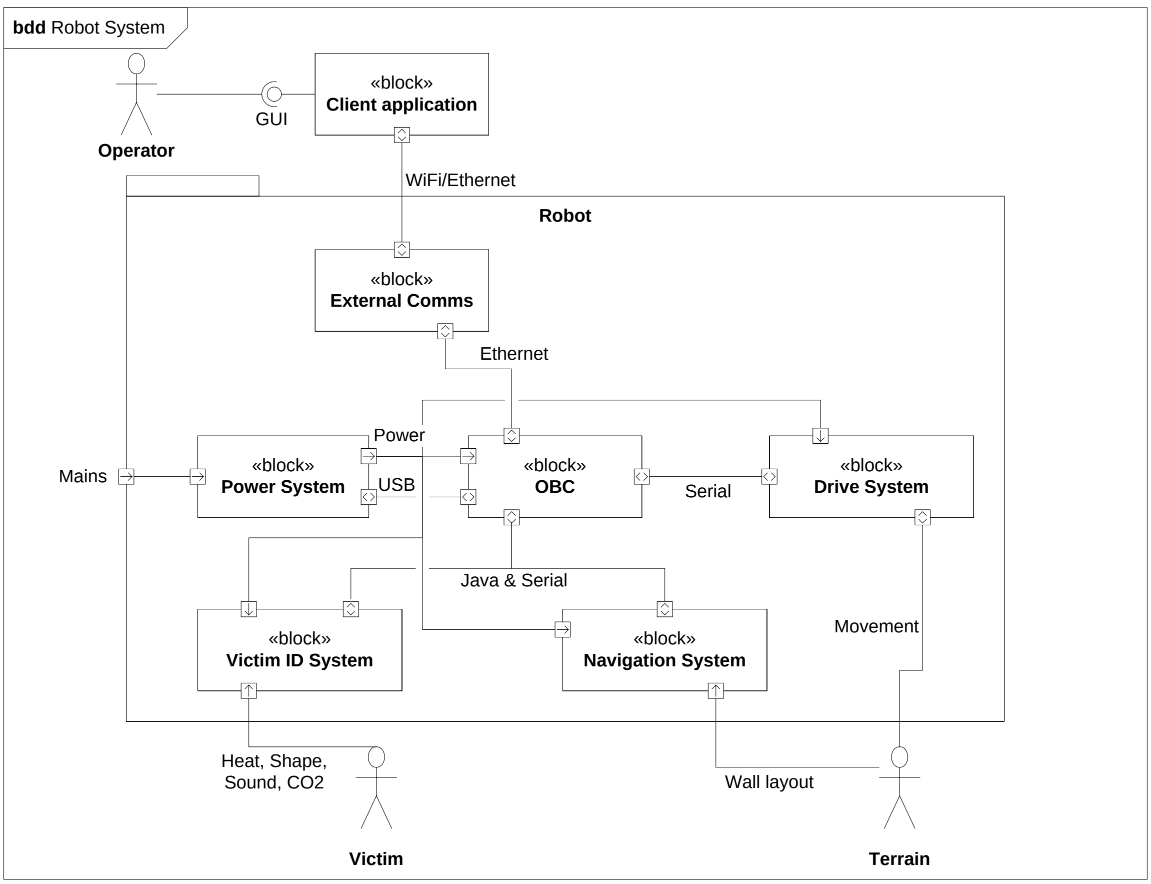


Figure 3-1: Systems Architecture Block Definition Diagram

3.2 Mobility

The centre of mass problems with the 2008 robot identified early that a rear flipper set would be needed to negotiate the tough obstacles. This leads to a drive system with four motors; two for drive and one for each flipper set. Each motor requires and encoder and a speed/position controller.

3.2.1 Stability

Stability in the robot is key to the success of the design, in terms of both the requirements capture and in order that the robot provides a firm and steady base from which feedback from the sensors can be gained. A chassis with poor stability will make manual data interpretation more difficult and automated data analysis less reliable. The 2008 chassis was a strong starting point, with a low CoM, rigid body and compact component packaging system, for these reasons it was deemed to be a good opportunity for development rather than redesign.

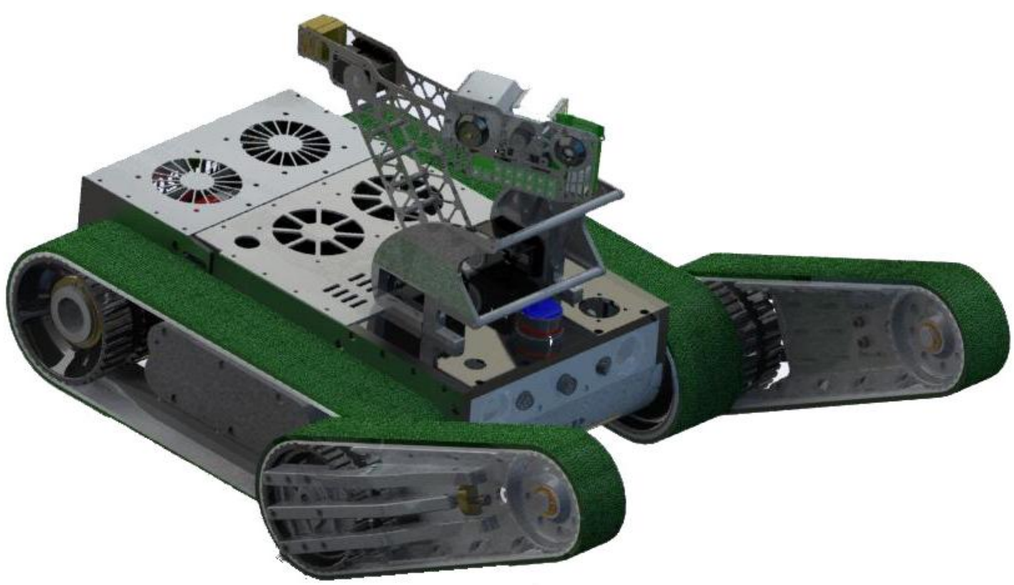


Figure 3-2: The 2008 Robot

3.2.1.1 Wheelie bar at the rear:

This option may have formed a quick fix to the problem of toppling over the rear when climbing. The main concern with it as a final solution was the lack of drive the wheelie bar would provide in a situation where it is the last point of contact as the robot climbs. A passive wheelie bar system offers significantly lower mobility improvement than a driven flipper system.

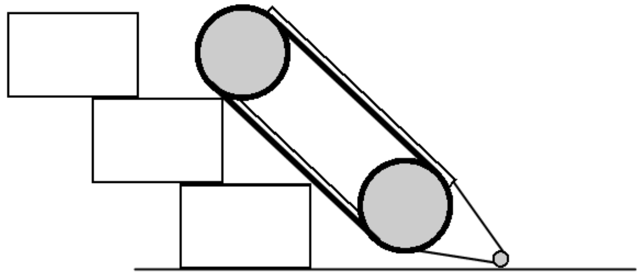


Figure 3-3: Wheelie bar design idea

There are issues with the possible design in Figure 3-3. These include the possibility of the cross bracing bar locking or snagging onto the step field blocks. With no rear flippers this would create a situation which would be very difficult to overcome. A protruding bar from the rear would also increase the size of the robot outside of the turning circle making manoeuvring difficult in tight spaces such as the 1.2 x 1.2m grids in the competition. Manoeuvrable rear flippers are advantageous to keep the robot footprint small.

3.2.1.2 Flipper Options

Figure 3-4 provides concept designs for flipper options. The existing single flipper design is provided with flipper extensions considered and

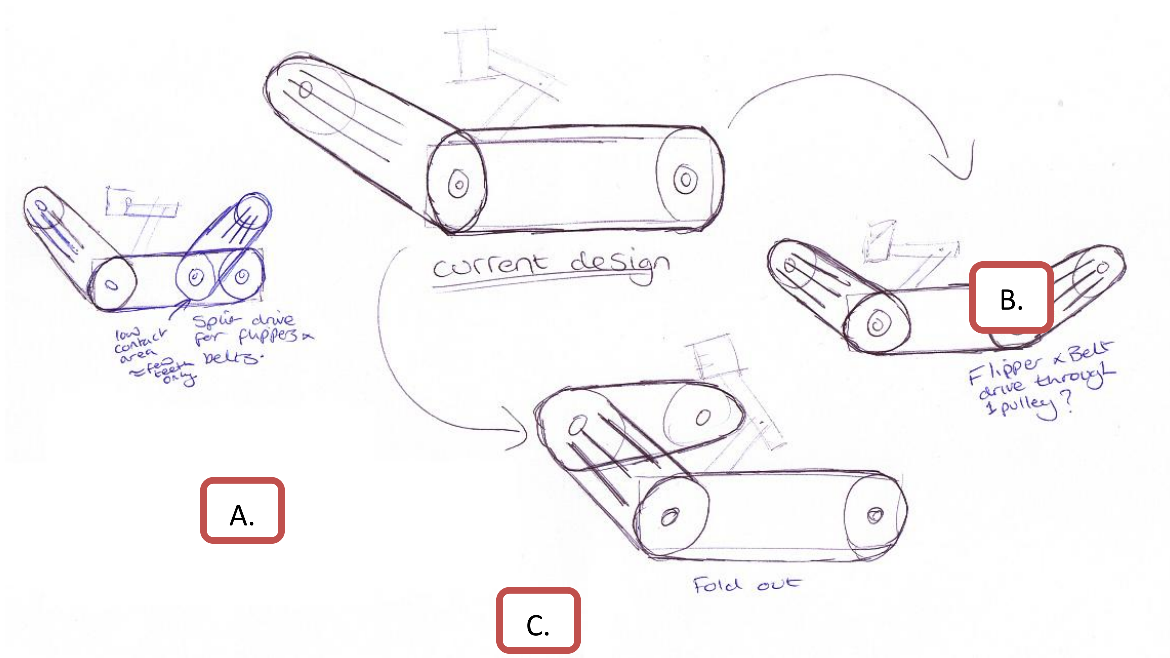


Figure 3-4: Preliminary concept designs

3.2.1.3 Extension of current flippers

The development of current flippers with an extension system as in Concept C in Figure 3-7 shifts extra mass to the front of the robot and provides lock over steps.

Limiting Factors:

1. Powering the secondary extension flippers would either require a running belt / chain system or the housing of the motor within the flippers itself. This would require power and control wires to be run the length of the first flippers.
2. A large increase in maximum torque and power would be required to move, in a controlled manner, the extra mass in the flippers.
3. The new flippers would have to be located offset from the current pair, adding another 100mm (2 * 50mm tracks) to the width of the robot in its most compact form and 8cm to the minimum turning circle.

3.2.1.4 Additional rear flippers

A set of rear flipper provide lift over obstacles and greater capability for maintaining traction whilst beginning climb of steep obstacles from flat or uneven terrain (Figure 3-5).

Figure 3-5: Stepfield run up to 45° ramp

A. To maintain the compact form of the current machine the new flippers could be located between the current front and rear pulleys.

Limiting Factors:

1. A very low contact area exists for drive from the main belt to the secondary flipper belts, only around three teeth on each side of the compound pulley.
2. The volume required to house the new flipper shaft and drive motor is currently fully utilised by the central computer components.
3. Wiring for the motor control board and housing of the board would require more space within the chassis.

B. The new flippers could be driven through the current drive pulleys, minimising the required size change on the chassis.

Limiting Factors:

1. The new flipper drive motor would have to be located away from the main belt drive motors as insufficient room is available within the current chassis boundaries.
2. The main belt drive motors are currently situated in the path of any flipper shaft and would have to be relocated. For this to be a viable option a third set of pulleys would be used for drive power to the belts. Possible locations for the new drive pulleys will need to be identified.

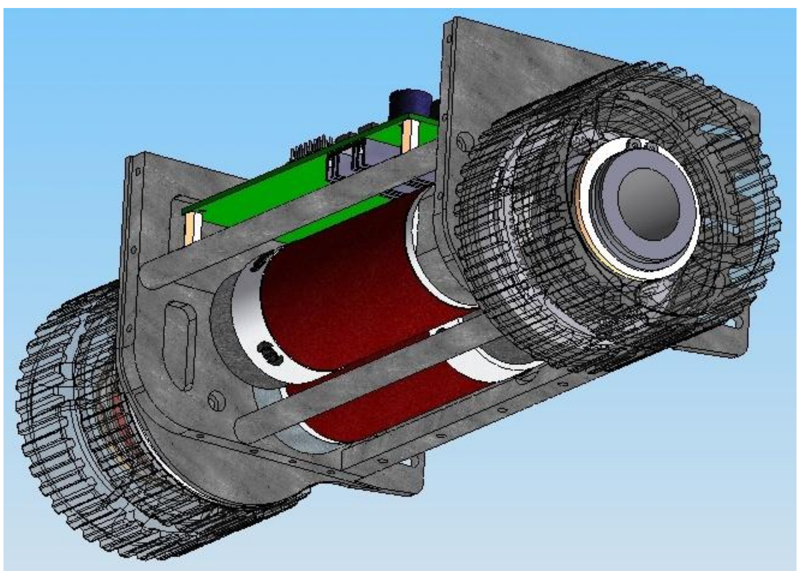


Figure 3-6: Tight packaging of rear drive compartment

3.2.1.5 *Flipper Decision*

Option A was identified as the preferred option since the robot footprint has little change maintaining the ability of the robot to turn easily within one arena tile.

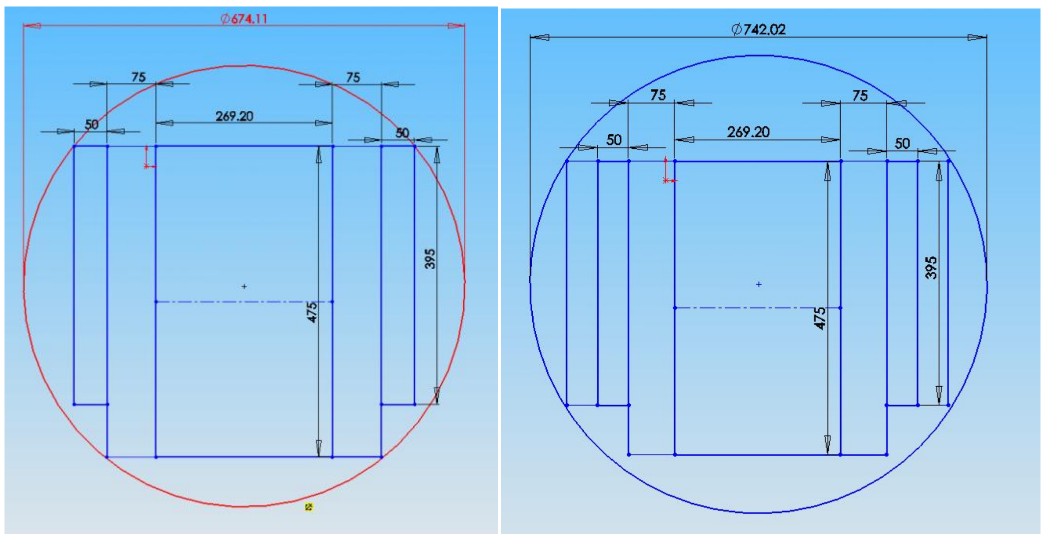


Figure 3-7: Comparison of turning circles with additional flippers

360° rotation is also a requirement of the flipper arms which since the 2008 front flippers had an inconvenient dead zone.

This limits the arm length in order to provide clearance for the track profile of the other flipper pair.

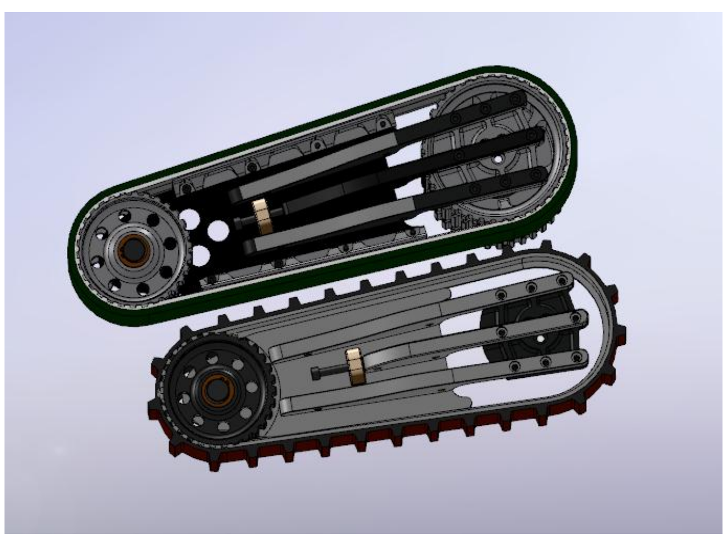


Figure 3-8: Flipper arm length comparison

As visible in Figure 3-8, the arm length will decrease from 300mm to 258mm (pulley centre to centre distance).

In order to utilise as many existing parts as possible, the outer support arms will remain the same and instead only the inner arms used for tensioning and the plates will be altered.

The tensioning system, remaining the same, allows for ± 2cm of belt tensioning play from the specified length. This is to account for manufacturing tolerances and stretch during the run in period.

Another key requirement is reliable transmission of torque from the flipper motors to the flipper shafts for the rotation of the flippers. This will aid both the stability and mobility of the robot over all terrain. The problem to overcome is the shearing and stripping of the current timing belts during operation. A simple system of a chain and sprocket is proposed which will allow transmission of this torque with a much smaller possibility of slip and almost no possibility of failure of the. A simple system was desired which allowed for improved control and drivability with the key aim of leading to a 'best in class mobility' chassis. Again the specification is developed below:

3.2.1.6 Specification for the flipper design

- Provide a means of descending smooth and controlled descent of a step drop of 0.25 m.
- Be able to fit within the footprint of the robot.
- Maintain the centre of mass of the robot within the flippers extended footprint whilst climbing stairs and slopes.
- Allow the robot to run on flippers only
- Transmit rotation from flipper motors to flipper shafts (1:1)
- Allow 360^{o} rotation of flippers
- Transmit 40 Nm torque without failure or slip

3.2.1.7 *New Design*

From the outset it was seen that the current flipper arm design is strong. For the new flippers the overall form and function shall remain although the sizing will be altered. The requirement for change is that 360° rotation is desired for the flippers. Although this is not possible for the front flipper due to the Hall Effect encoder used, it shall be possible with the quadrature signal encoder used on the rear flipper system.

The three concept designs in Figure 3-4 were created with the main criteria of maintaining as much of the initial chassis as possible.

3.2.2 Drive Systems

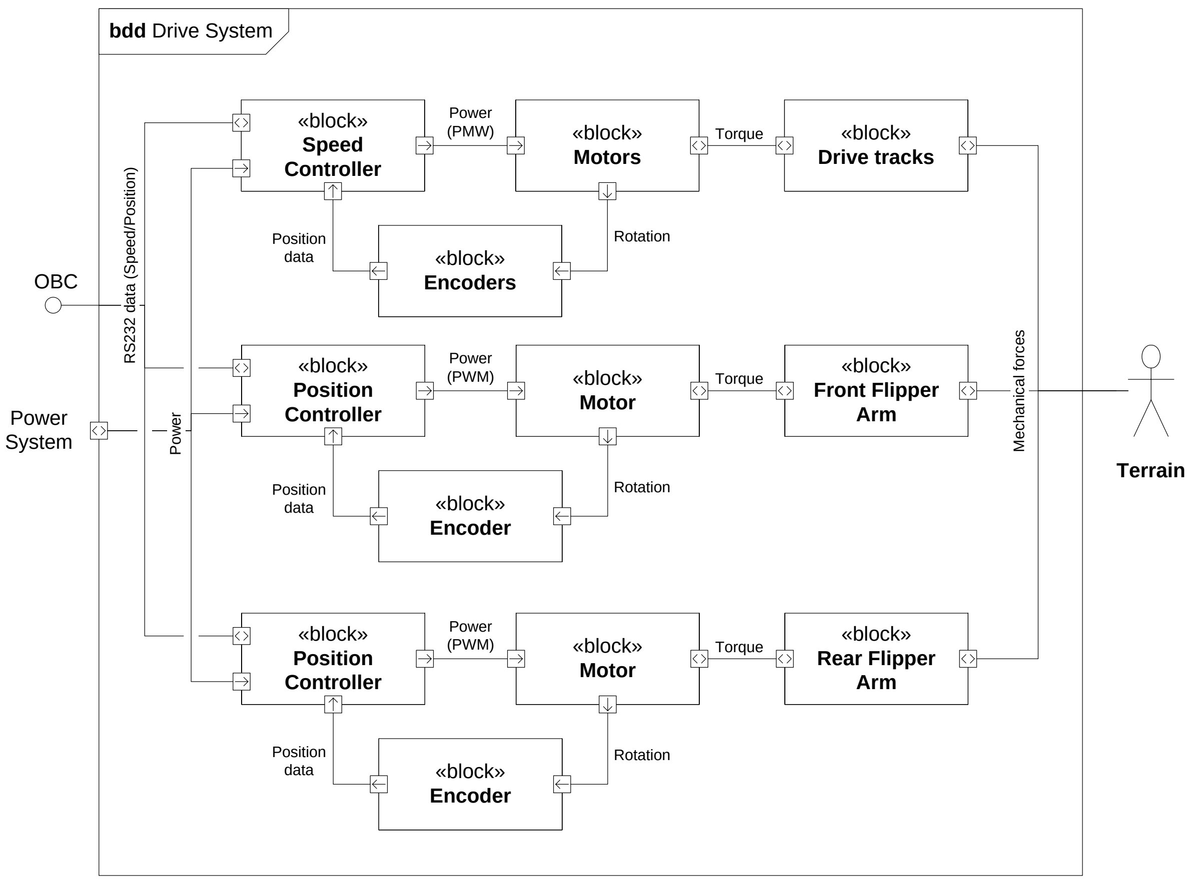


Figure 3-9: Drive System Block Definition Diagram

The drive system should provide lasting traction over all terrain in the competition, including carpeted and uncarpeted ramps and the most challenging step fields. To achieve this goal a number of solutions and designs could be implemented.

The drive train (including drive motors and geared connection to drive pulleys) in the 2008 competition performed fully to the specification and therefore there is little need to develop this subsystem further. However, the speed controller operated in open-loop configuration providing power control. It was decided that this was less preferential in the arena. Power control can be used to increase speed on flat sections by providing more power. For high power applications and obstacles, such as the stair set climbing and the 45° slope climb, this would likely involve applying full power to the tracks while travelling at lower speed. When the obstacles have been overcome there is a risk that the controller will not back off the power fast enough causing rapid movement over flat ground leading to damage to the arena or robot.

For the new design a speed control system with open loop control shall be used. Feedback from the motor encoders shall be used to ensure the motors are driving at the speed requested by the controller. In high load obstacles, the power is increased to maintain the speed requested. During low load obstacles the power required for a given speed will be lower and the control boards will provide this as appropriate.

The tracks are a major subsystem of the overall drive system, allowing the drive train to develop all power needed over any terrain. The ’08 tracks met this need over flat terrain and to a certain extent over the more difficult terrain, however they degraded quickly when encountering step fields. Also of consideration is whether track design can increase the mobility over stair sets.

3.3 Power Systems

The main components of the power system are the power source, batteries, and a distribution system around the robot. The power system also incorporates the emergency stop system.

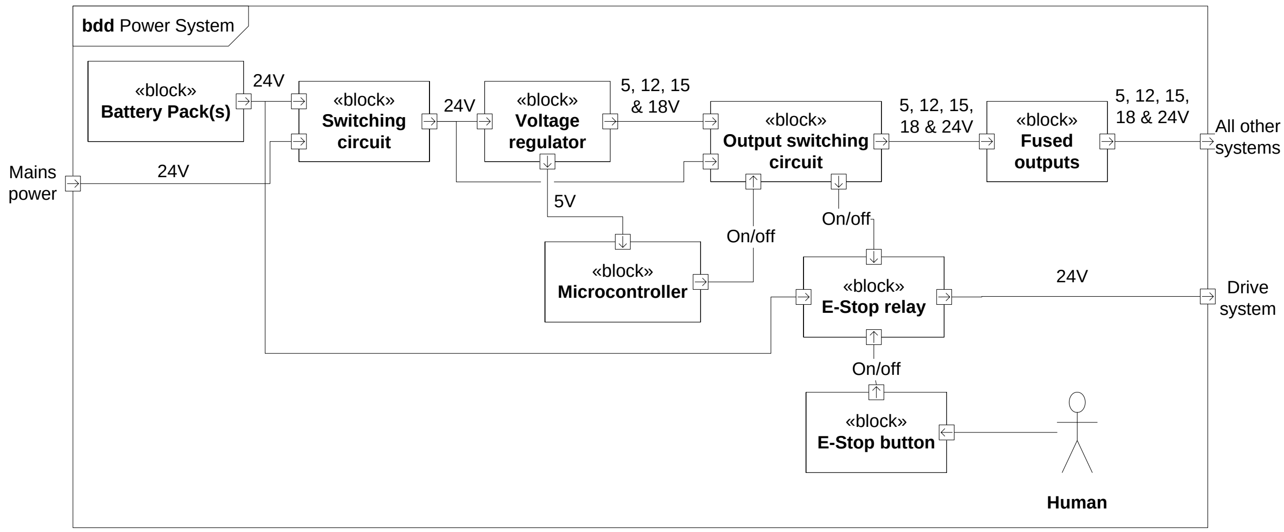


Figure 3-10: Power System Block Definition Diagram

3.4 Manipulation

The griper must provide means for picking, moving and placing small objects, some of these objects include an eye through which a rod could be placed to provide easier means of picking the objects up.

3.5 Victim Identification

For a search and rescue robot locating victims is of great importance. A robot for RoboCup Rescue must locate victims in both autonomous and tele-operated modes.

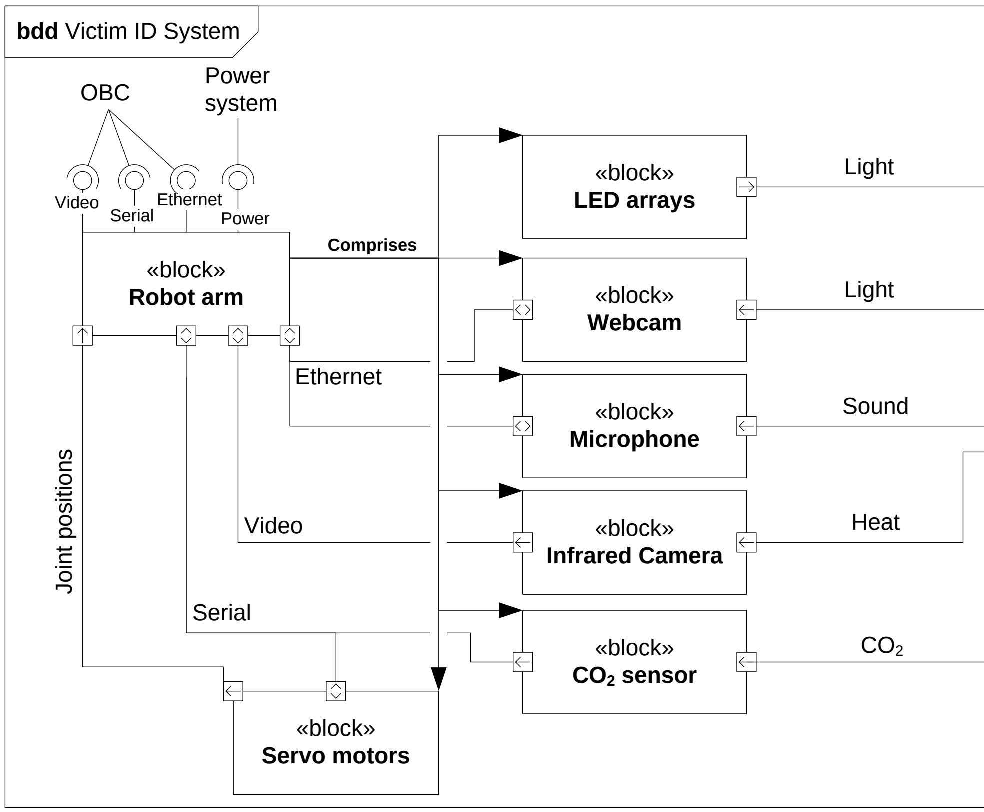


Figure 3-11: Victim Identification Block Definition Diagram

3.5.1 Tele-Operated Identification

All signs of life can be observed when tele-operated and must be displayed to the operator so the operator can make a decision. The onboard computer relays the information to the client which is then displayed to the operator.

3.5.2 Autonomous Identification

The onboard computer receives information from all sensors and can make decisions on the possibility of a victim. Only one sign of life has been specified as detectable.

3.6 Navigation

The navigation system is broken down into autonomy and tele-operation, representing the two modes of operation at the competition.

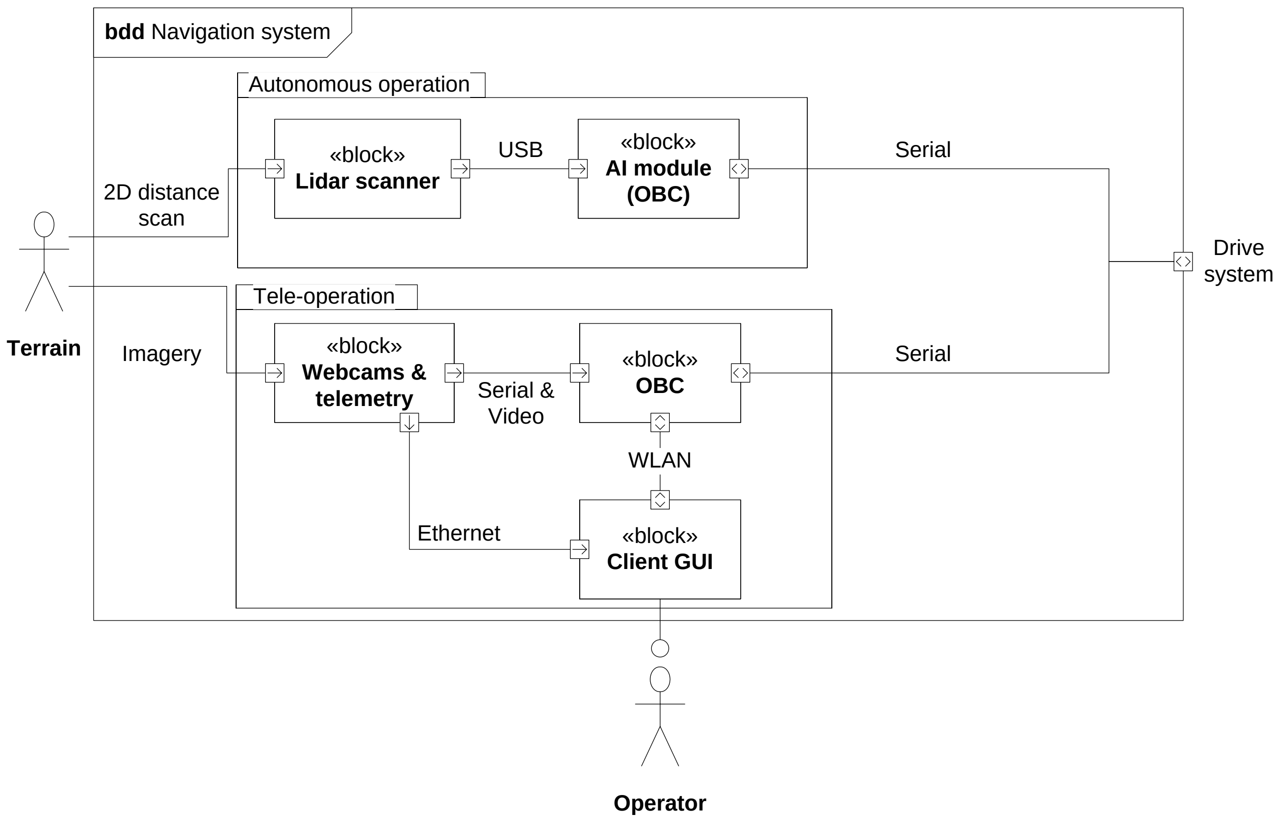


Figure 3-12: Navigation System Block Definition Diagram

3.6.1 Tele-Operation

The systems used to inform the operator of the robot's state and signal the drive system. This comprises of the webcams and other sensors such as LiDAR and sonar, together with the robot computer, client computer and communication.

3.6.2 Autonomy

LiDAR and sonar is used to detect obstacles. From this information the robot must navigate itself around the arena. Victim identification must be carried out automatically using the sensor set on the robot.

In order for the robot to autonomously detect victims, it must be able to differentiate them from its other surroundings. There are a variety of signals given off by victims which the robot's sensor systems can detect. However each of these has advantages and disadvantages when used in an autonomous context.

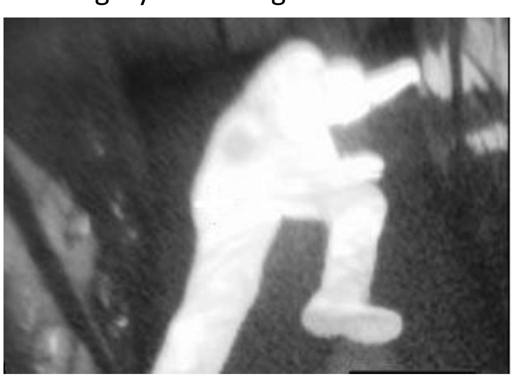
	Advantages	Disadvantages
Shape (form)		Variable lighting conditions and enclosed locations of victims makes obtaining adequate images difficult
Movement		Requires robot to be stationary.
Heat	Easy to spot human range heat signature and process into target	
Sound	Non-directional so orientation of sensor less important	High likelihood of interference from crowd/external noise
CO_2	Non-directional	Needs to be close to victim for reliable reading without expensive highly sensitive sensors

Searching for the heat signature of potential victims using the FLIR thermal imaging camera was seen as the most promising and achievable method to be investigated and developed.

The FLIR thermal camera as used in 2008 can be set to output a simple greyscale image where the brightness of each pixel corresponds to temperature. By setting a threshold value for this brightness, objects of a specific temperature range can be extracted.

3.6.2.1 Steps for autonomous victim identification

1. Obtain greyscale image from IR camera



2. Run threshold over image to isolate human temperature range and produce black & white image.

3. Run blob detection algorithm to find size and location of hot areas.

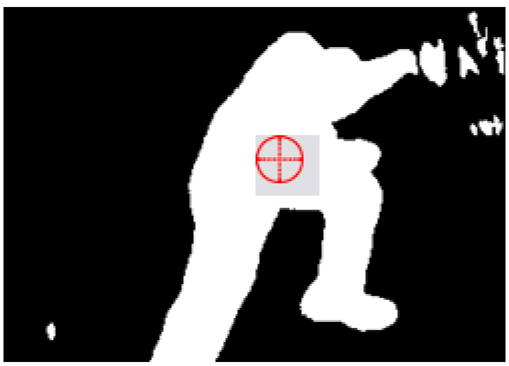


Figure 3-13: Blob detection stages

A GUI to monitor and adjust the parameters of the blob detection algorithm was seen as important to the calibration and operation of the software.

3.6.2.2 Autonomous navigation

In order for the robot to autonomously navigate around its environment it must gather data about the nature of its surroundings and make movement decisions based upon this data. The robot is equipped with a range of sensors with which to gather this data but the Lidar and sonar sensors were seen as the most applicable to the problem of navigation.

The LiDAR (Light Detection And Ranging) sensor was quickly identified as the most powerful tool for this function, as it produces an accurate 2D scan comprising the distances to 682 discrete points across its 240° range at 100msec intervals. This is also the primary method of autonomous navigation used by other similar autonomously navigated mobile robots used in industry and research.

Figure 3-14: LiDAR unit for robot(6)

The sonar modules can also provide useful information about the robot's surroundings but it was decided to focus less on these sensors as they have disadvantages compared to LiDAR in terms of accuracy and resolution. Reflections of the ultrasound from uneven surfaces can also cause spurious results.

Although it was decided to focus upon LiDAR as the primary ranging sensor, a conscious effort was made to ensure that any navigation solution was flexible enough to incorporate data from other sensors at a later date, if deemed necessary.

3.6.2.3 PieEye

After a series of brainstorming sessions, a flexible navigation tool was devised as an abstract software concept, affectionately named 'PieEye'. The tool works by dividing the ranging data received from the LiDAR sensor into equally sized 'slices' throughout its range. The distance data points within each slice are combined and weighted to give each slice a value for the AI software module to use when deciding on which course to steer. A similar method was devised to detect collisions using adaptive thresholds.

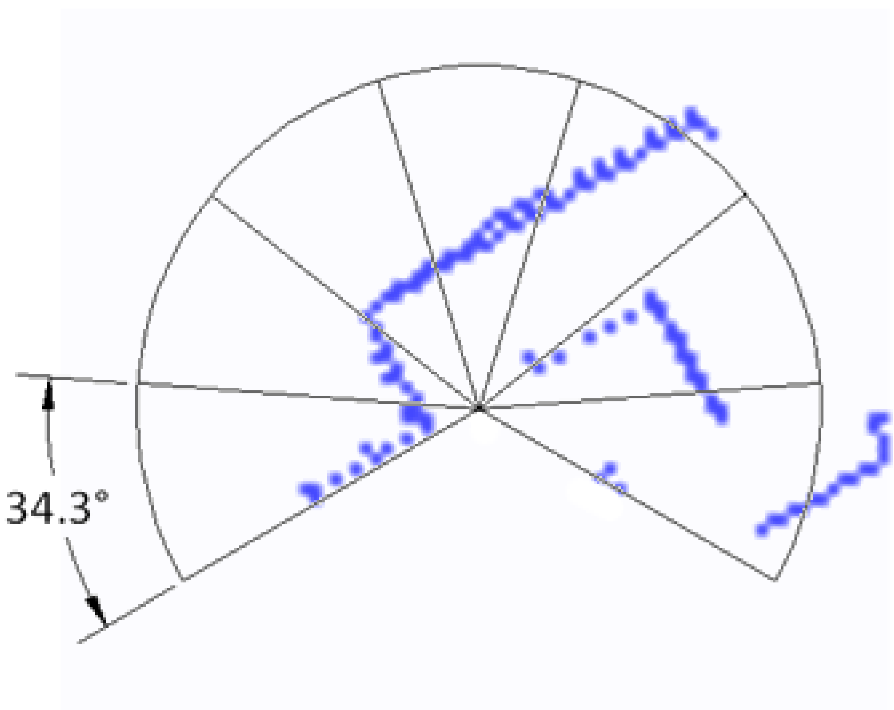


Figure 3-15: PieEye illustration

- A reactive style navigation method which outputs the best course to steer.
- The decision logic resembles that of a multi-layer neural network, of which the weightings are currently set by hand.
- The LiDAR scan is simplified by averaging measurements into groups ("slices"). Each of the slices being an input to the neural-net style structure.

3.7 Mapping

The robot uses the LiDAR unit to produce a map of the operating terrain. This is built on the onboard computer and passed back to the operators computer and displayed.

3.8 Testing and Development

To ensure each subsystems success can be measure against its specification already stated and the overall specification of the robot one must be able to split the full robot system into component subsystems (where possible) to allow individual verification of this system. Modularity within the full system is essential in the prototype design stage to allow problems to be isolated and solved within subsystems. To this end, it is proposed that there will be three discrete modules which can be tested and built separately:

The front module will house the front flipper shaft and flipper rotation drive motor with LiDAR and sonar sensors also housed in this module. It will be possible to drive the flipper motor through using the central module, or through a separated motor control board attached to a computer.

The central module will house many of the major electronic components in the robot. These include the motherboard and hard drive, power distribution board and front flipper motor control board, the wireless network router and connection points for USB devices, VGA monitors and Ethernet cable (to hardwire the network if necessary). This central module will be accessible from the top of the robot and must be removable as the central chassis is fixed to the front module.

The rear module houses both drive motors and the rear flipper motor along with drive motor and rear flipper motor control boards as well as a rear facing webcam. As this module is used to tension main drive belts the chassis for this module must also be detachable.

The robot arm creates a simple module which can be detached from the front and central chassis, through use of a 'Dynamixel' control board, the servomotors on the robot arm have the ability to be driven with the robot arm module disconnected from the robot itself as required.

The arena facility in the competition is based upon a 1.2m x 1.2m grid layout. For this reason a test area will be constructed within the lab allowing for analysis of performance to be carried out on the robot's manual control and autonomous functions.

The test arena shall be developed from official plans from the RoboCup competition. Each stepfield shall be constructed as below, from lengths of 4 x 4 inch pine timber.

Each unit shall be reconfigurable into either a red or orange stepfield in order provide a range of testing opportunities.

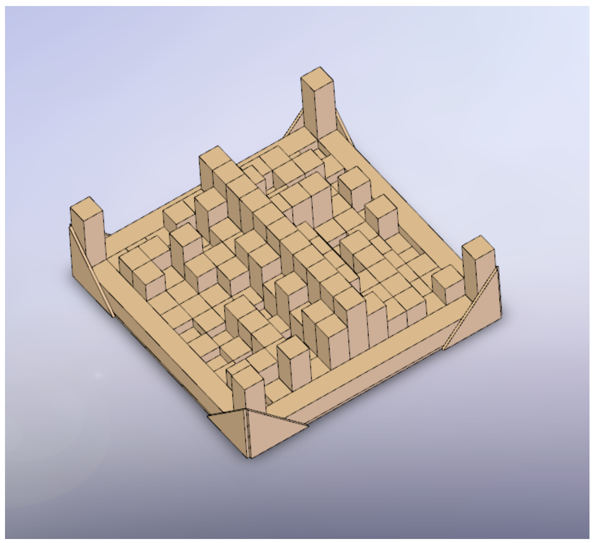


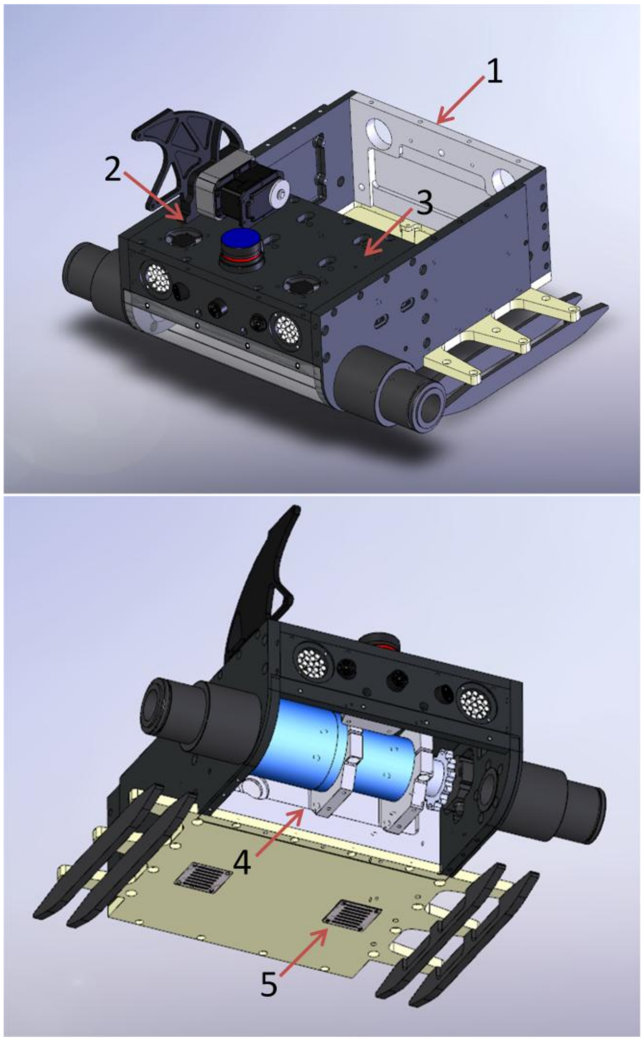
Figure 3-16: Typical Red stepfield arrangement

4 Subsystem Design

Subsystems have been designed and specified with specifications developed in this section.

4.1 Chassis

Analysis of the 2008 design from last year's competition demonstrated a strong starting point with the current chassis. For this reason only minor changes will be made to the majority of the front section panels.



1. Material removed for computer case clearance
2. Wider spacing of rollcage
3. Additional LED fan
4. Extended slots for cable management
5. Base fans for CPU cooling

Figure 4-1: Chassis analysis

4.2 Drive System

4.2.1 Tracks

An early consideration in the drive system re-design was the effectiveness of the 2008 'Rough-Top' tracks. These tracks provided incredibly good grip on flat surfaces with minimal slip. However, when used on larger sloped obstacles ('red' step fields and stair sets) the lack of a positive mechanical lock between left and right tracks introduced uncontrolled slip making robot direction difficult to maintain through remote operation. Therefore the major amendment to the design of these tracks will be to add a mechanical lock to the tracks to reduce the possible slip to a minimum, making remote operation much more intuitive.

A number of ideas were considered in the design process of this sub system, all aimed to provide the mechanical locking of the tracks on stairs and step fields. The first of these was to provide a custom backed timing belt with high density foam protected with a deformable rubber compound layer, otherwise known as a 'Combitex' backing, refer to Figure 4-2. The backing would be intended to deform to the feature shape and therefore provide the necessary positive mechanical locking.

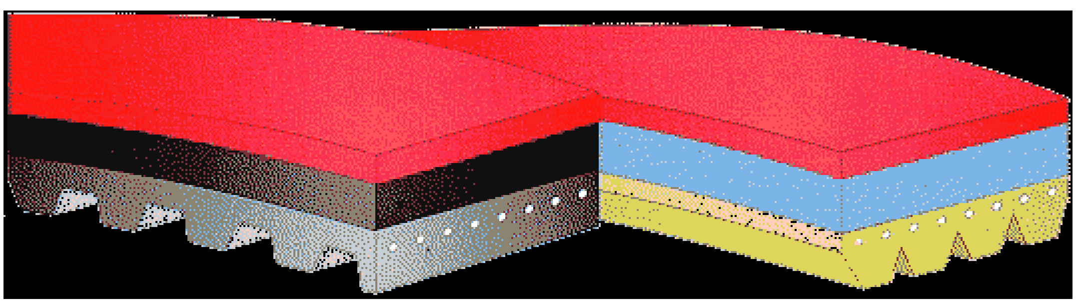


Figure 4-2: Examples of Combitex Backing(7)

Although this method would provide some mechanical locking it would not provide this locking if direct pressure was not added to that particular section of the track. So, if the robot was stuck with all weight on one track the opposite track would simply slip and not aid the forward motion. Therefore a system which included a flighted profile added to the polyurethane tooth profile was considered. The profile for this design should allow mechanical locking of the belts over step fields and stair sets. Therefore the dimensions of these profiles are critical to the success of the belts. The profile was designed to perform in a similar manner to the Remotec 'Wheelbarrow' tracked robots (though on a smaller scale) and after discussion with Thistle Belting (MoD standard robot belting supplier) and Transdev (UK based manufacturer) a profile was finalised.

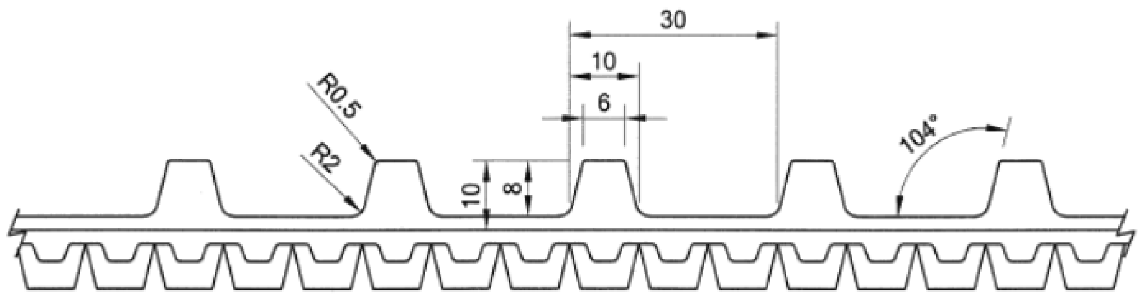


Figure 4-3: Custom Backing Profile

Figure Figure 4-3 illustrates the final backing profile, allowing for positive lock on obstacles in the arena and also minimising allowable slip between profiles. At this stage two design options must be analysed to find the optimal solution. Firstly to produce the tooth profile in polyurethane which would be heat welded to the standard T10-K13 profile in place of a PVC or rubber backing. This option would lack grip over normal terrain and would therefore require addition of some high friction material to the top land of the tooth profile above, fixing this top material would be problematic and time consuming for all belts used on the robot.

The next option to produce this tooth profile is to use a custom machined rubber backing. In order to achieve this a 10mm rubber backing would be adhered to the T10 profile and then all but the teeth would be machined away (as illustrated by the hatched area in Figure Figure 4-4 below).

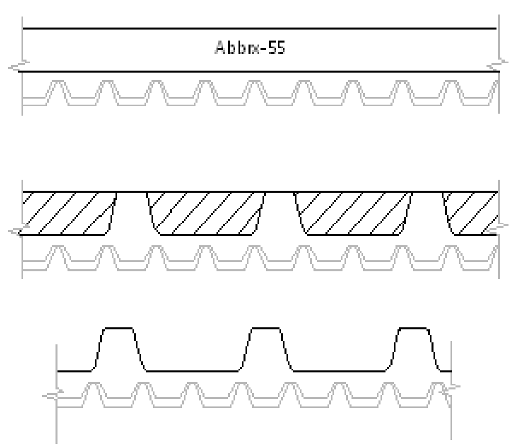


Figure 4-4: Illustration of the machining necessary to produce the custom profiled tracks

This solution is comparatively expensive, but allows any profile to be produced for the best compromise of friction and durability of the belts. The material chosen for the backing is Abbrx-55 (a trade name of the Transdev company), a silica reinforced natural and synthetic rubber with high abrasion resistance and good friction properties. Figure Figure 4-4 shows the final belt profile and design.

Table 4-1: summary of benefits of track designs

Belt Type	Rough top	Combitex	Polyurethane profile	Rubber Profile
Yellow arena	Very good	Very good	average	Very good
Orange Arena	Very good	Good	Poor	Very good
Red Arena	Average	Good	Poor - average	Very good
Cost	£500	£700	£500	£1400

4.2.2 Speed Drive Control

Using speed control on the drive motors leads to more intuitive operation and greater precision when negotiating rough terrain and was identified at the 2008 competition as a necessary feature. It also allows the robot to hold itself at zero speed on a slope.

The drive motors feature and optical relative encoder similar to the one fitted to the new rear flipper motor. The ax3500 control board has built in PID (proportional-integral-differential) control. Setting an integrator in the controller leads to zero steady-state tracking so the speed set by the operator is the speed the robot runs at (with constant scaling factors). Established PID tuning techniques such as Ziegler-Nicholls(8) were attempted but the slow rotation speed meant that it was difficult to use. In the end the coefficients were adjusted to get desirable characteristics. High P coefficient allows for the greatest top speed and the D coefficient was added to compensate for the overshoot introduced by P and I and reduce the settling time.

A problem with the ax3500 control board was that when in closed-loop mode it shut down the motors and triggered an error condition when no movement was detected after 0.5 seconds of running on greater than 50% power. This error condition was permanent and the control board had to be reset. This was problematic when the batteries where weak, so half power was not very high, and the robot could not overcome an obstacle. This safety feature meant that the motors would cut-out and the robot would become immobilised. Manufacturers Roboteq were contacted and they advised that new firmware would allow this feature to be disabled. When this new firmware was released it did allow the feature to be disabled but it also made the error condition temporary. Simply sending a fresh move command clears the error meaning that the benefits of the safety feature, not damaging the motors when they are stalled, could be used.

4.3 Stability

Specification:

- The robot shall be able to pass over the most challenging 'red' step field designs of the competition.
- The centre of mass of the finished chassis shall be located to allow forward and reverse drive ascent and descent of stair sets and 45° ramps.
- The 2009 robot should be capable of step changes in platform height of 25cm with smooth transition (i.e. no drops should occur whilst the robot makes contact with the next running level)
- The flippers shall be controllable over the full 360° range of motion, with clockwise and anti-clockwise stable and controlled movement.

4.3.1 Flipper Arm Design

Flipper arms are seen as key in the manoeuvrability of any robot. They allow a greater range of obstacles to be crossed as they provide design flexibility which can be tailored to the observed situation, from gap crossing to climbing and drops. The system architecture identified that rear flippers are to be developed (Section 3.2.1).

4.3.1.1 *Rear Section Modification*

Rear flippers located between the front and rear drive pulleys. It is clear from the tight packaging of the current chassis that it would not be possible to include a rear set of flippers, with drive system similar to that of the front, without an increase in the overall package size.

Alternate designs were attempted to maintain the single rear pulleys at the rear. These where eventually removed from development. The design for single rear pulleys would require the loss of direct drive between the drive motors and the pulleys. This was not deemed as acceptable for reasons including frictional losses, increased noise, lubrication issues and drive linkage complications.

Several locations were studied for the rear pulley (Figure 4-5).

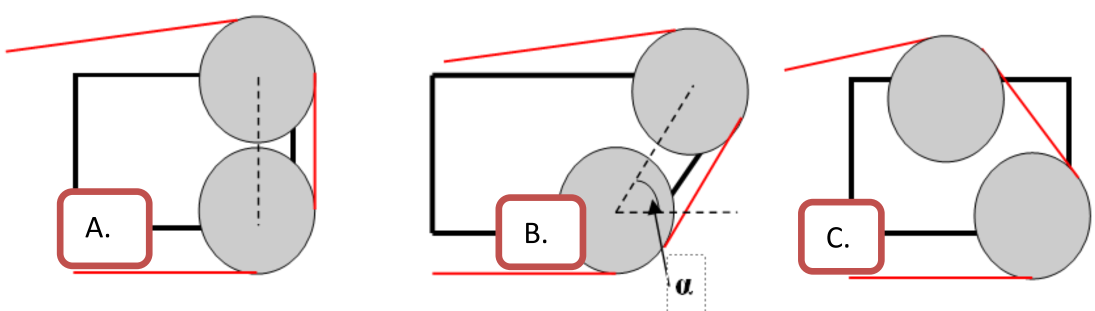


Figure 4-5: Drive and flipper pulley locations

All of the above options would provide sufficient wrap angle for drive of the pulleys given sufficient tension. Option A is preferable as the wrap angles are both a minimum of 90°. Option C would allow the footprint of the 2009 chassis to remain as small as possible but the smallest wrap angle is on the drive pulley, causing it to be the weak link in situations where high torque is required to move the robot. It would clearly be preferential for another, non drive pulley to slip first. This may create a situation where one of the flipper belts is not driven but the main tracks will still be powered. This is of paramount importance.

The advantages of B. are preferred. The alpha angle in B. can be used to provide a stable resting point for the robot during early stages of climbing of stairs, ramps and step fields. For this reason an alpha value of 45° was selected. This value is before the toppling point of the robot, and in line with the maximum slope gradient that the robot will be required to climb. Should the terrain call for a lower angle then the rear flippers can be moved to create a smaller angle 'sitting' surface.

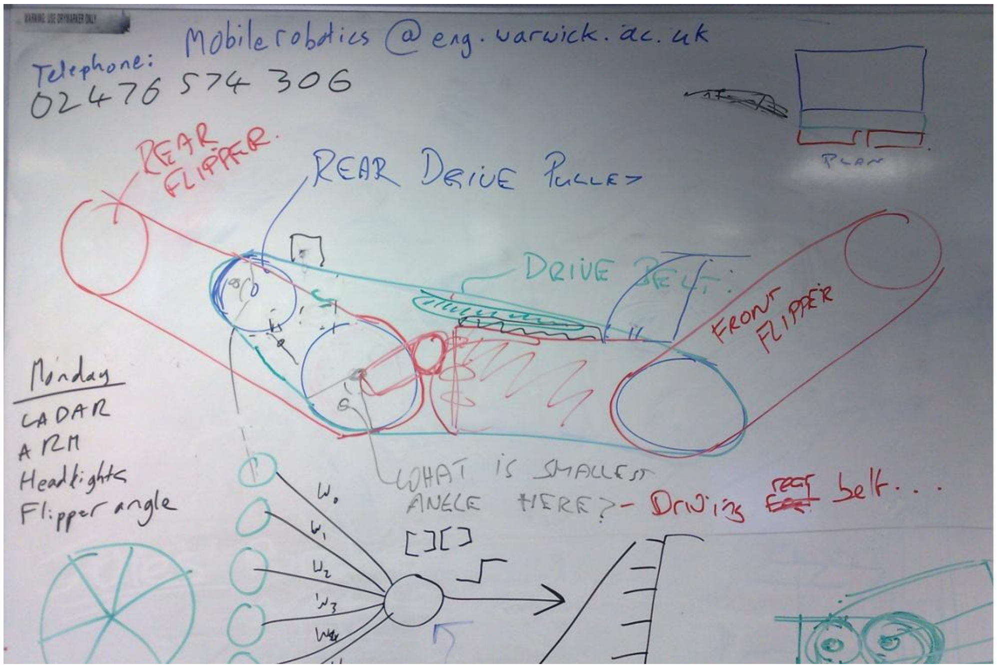


Figure 4-6: Whiteboard flipper and pulley layout

Various further design iterations were tried but a development of Figure 4-5(b) was chosen to proceed.

The second design phase required was the tensioning system for the robot main drive belts. The current flipper belt tensioning system is being maintained for the new flippers. The stem is simple and capable.

One issue that arose from the previous year was the tensioning bolt system. Bolts accessed from the central compartment where used to tension the belts by pushing on the rear section front plate. However, when the required computer equipment was installed the bolts became inaccessible and other means had to be used to maintain tension. Tensioning is an issue as it develops rolling friction across all the bearing surfaces. High levels of friction require higher powers to overcome them. As a reverse of this a slack system, although easy to run with low frictional losses, is prone to slipping and jumping teeth. From Figure 4-5 it is possible to see that the first pulley set to skip teeth would be the rear flipper system. This would result in drive loss on the flipper belts. In situations where the robot was on flippers only or pinned the loss of rear flipper drive may prevent the robot from being manoeuvred off the obstacle.

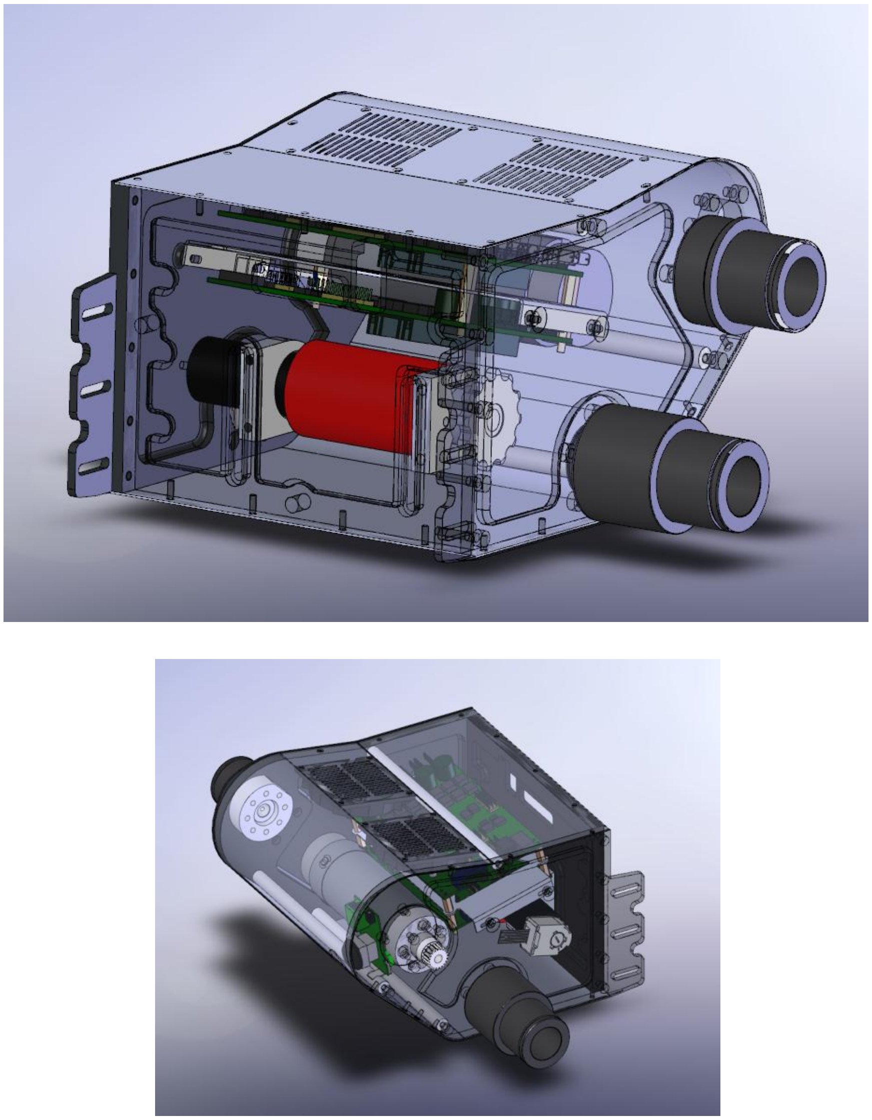


Figure 4-7: CAD modelling of rear section redesign

As shown above, the tensioning system is the same as the 08 robot. This allowed for a good tensioning range to compensate for belt stretch of up to 2cm on each of the main belts.

4.3.1.2 *The Final design*

As shown in Figure 4-9, the final design chosen was an adaptation of Figure 3-4, system A and Figure 4-5, B. The changes made ensure that sufficient contact area is created between all the pulleys in order to create an acceptable drive transfer.

The smallest featured wrap angle is 45° on the rear flipper compound pulleys and provided sufficient tension is placed into the drive belt system this should be adequate to drive the rear flipper belts. For the majority of situations, however, the front flipper belts and the main belts will be used to drive the system.

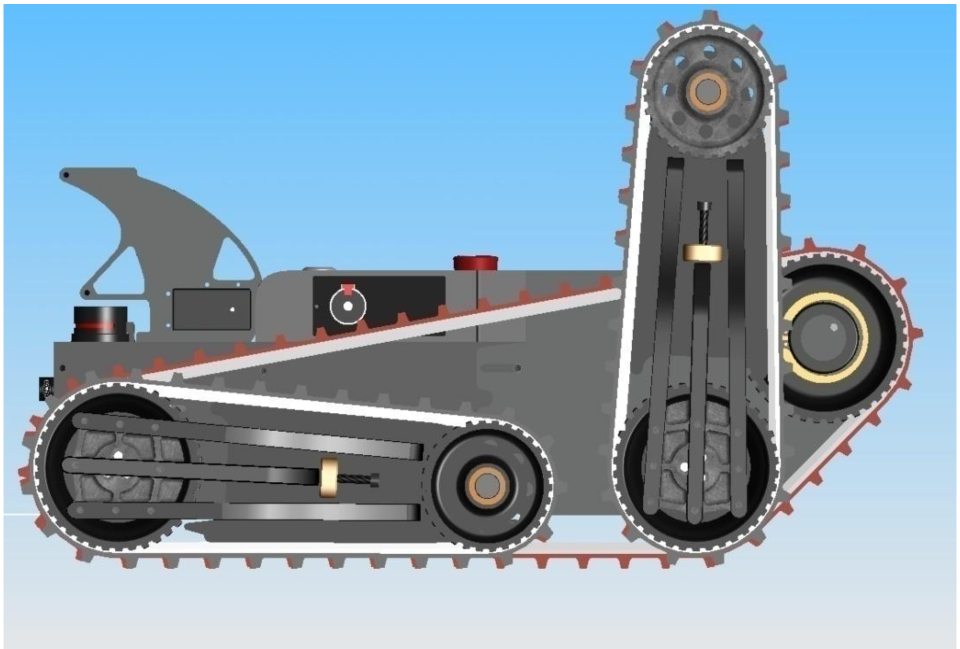


Figure 4-8: The new side profile view of 2009 flipper design in compact arrangement

The compact arrangement demonstrates the level of tolerance in the system for the belts lengths to change and to compensate for manufacturing errors.

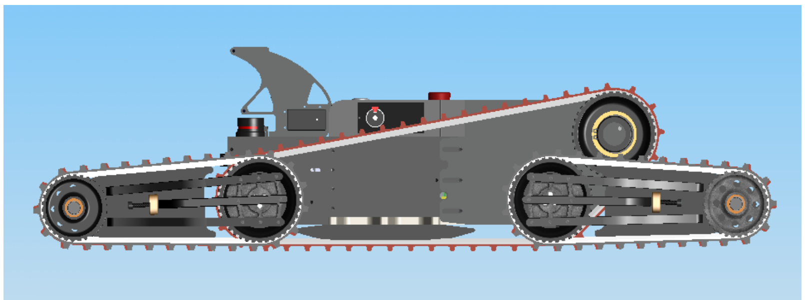


Figure 4-9: The new flipper design in its largest footprint arrangement

The main issue in creating the new design chassis was successful packaging of the new components for the rear flipper drive system. A physically small motor must be selected to fit in the chassis.

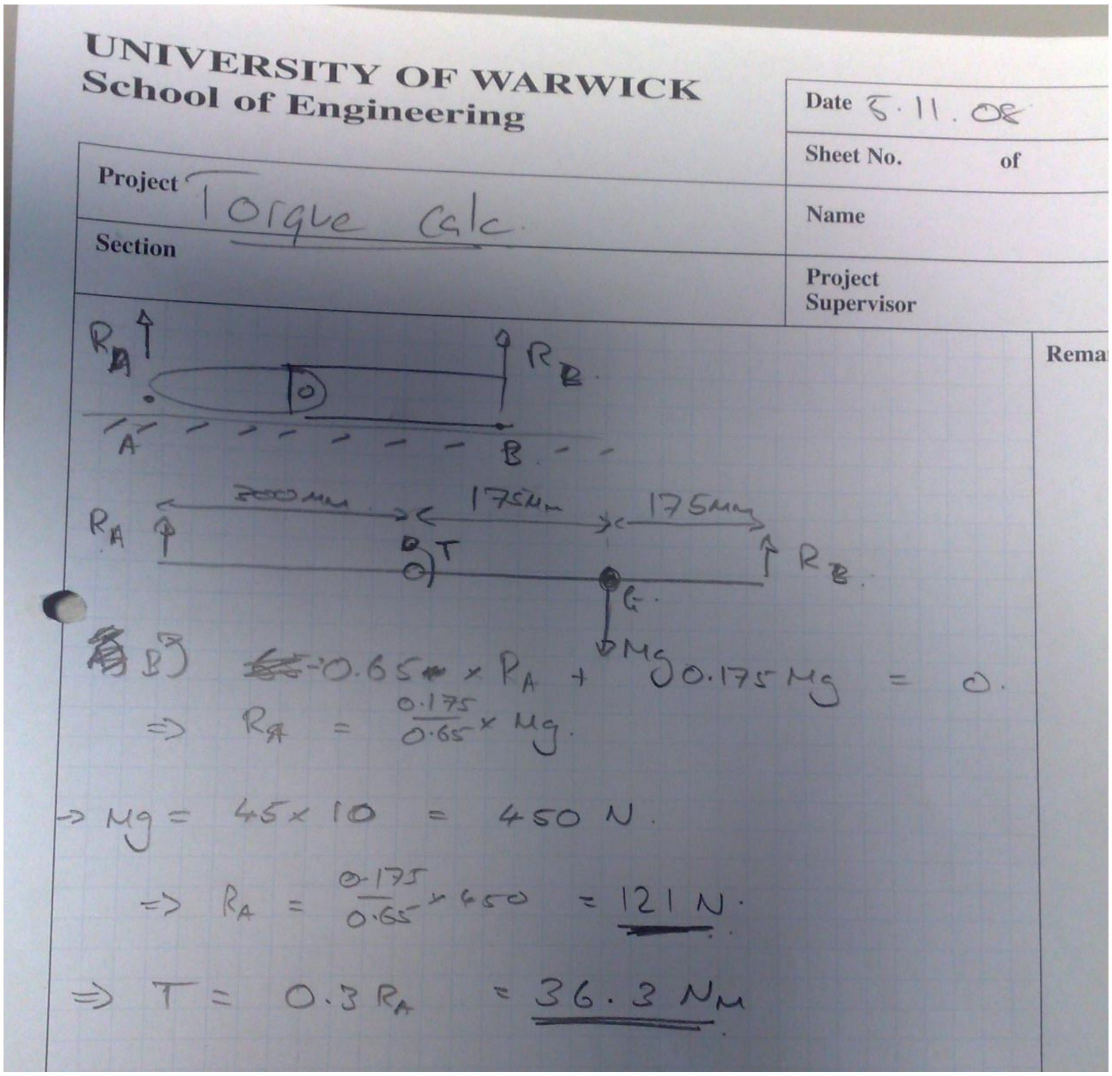


Figure 4-10: Flipper motor torque calculations

Figure 4-10 illustrates a simplistic torque calculation for the worst case situation where the flipper is lifting the whole body weight at full reach. This was used to specify the new flipper motor along with the size constraints.

Finite Element Testing of the flipper arms was undertaken to ensure that under loading the Nylon-66 would not deform beyond acceptable limits and would be within the yield stress of the material (40 MPa).

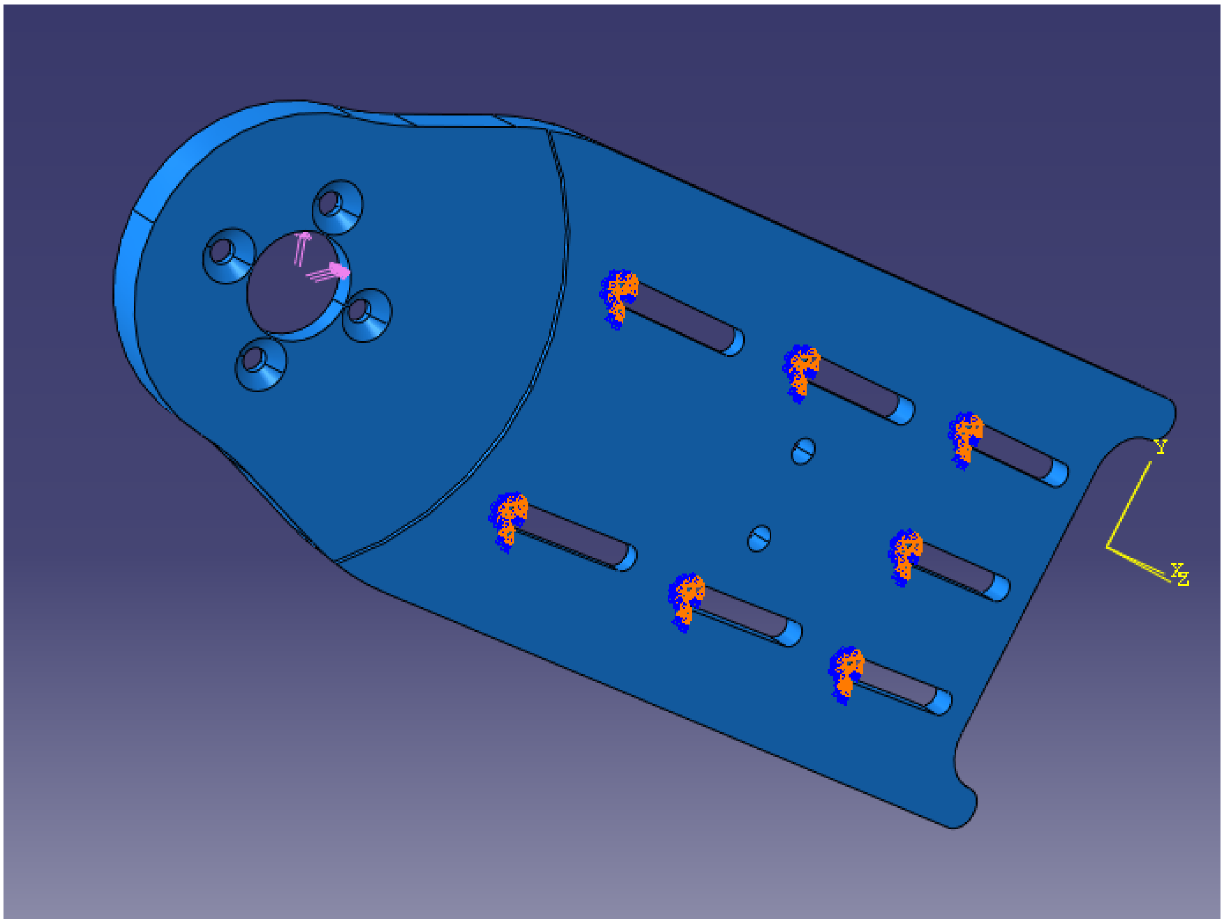


Figure 4-11: Load Parameters

Pressure of 0.0052 MPa (given from 45 kg static load) applied at the purple arrows with millimetres and megapascals the units for the analysis.

The part was fixed at the purple anchoring points highlighted in Figure 4-11 – this gives a reasonable estimation of the loading during lifting of the robot onto its flipper arms. It shows a similar situation to that described in the initial torque calculations.

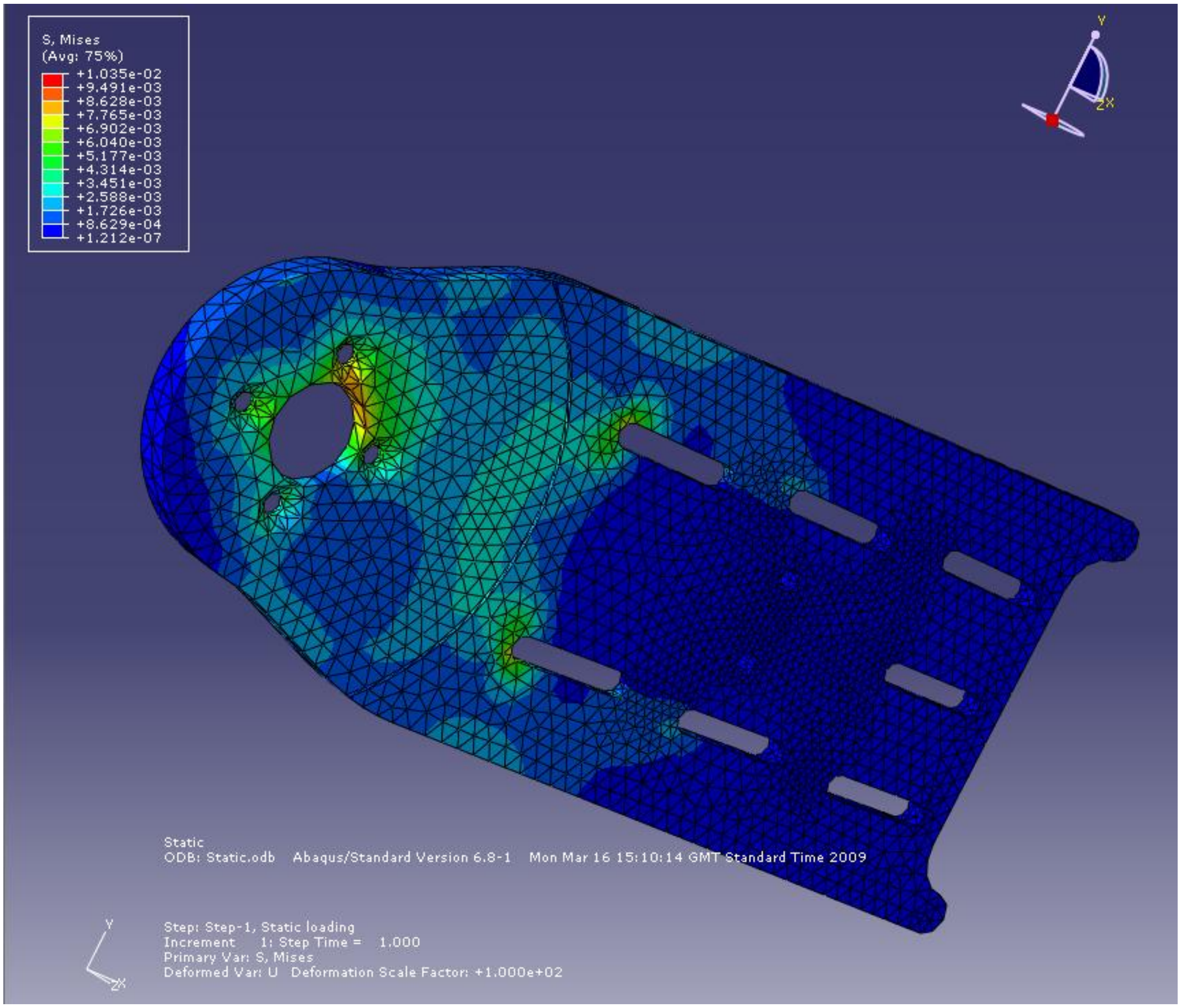


Figure 4-12: Flipper arm stress results

Figure 4-12 shows the stress distribution for the static load test the orange cells show a region of 8.7x10^-3 MPa stress – yield stress of Nylon is 40 MPa. This highlights the fact that there is a large factor of safety for the static loaded case. However, drop tests for a standard height should be undertaken to see the effect of the higher load associated with drop tests.

Also planned are drop tests and tooth stress tests for the polymer pulleys – all three sets will be analysed in the final report to verify that acetal is an OK material to use.

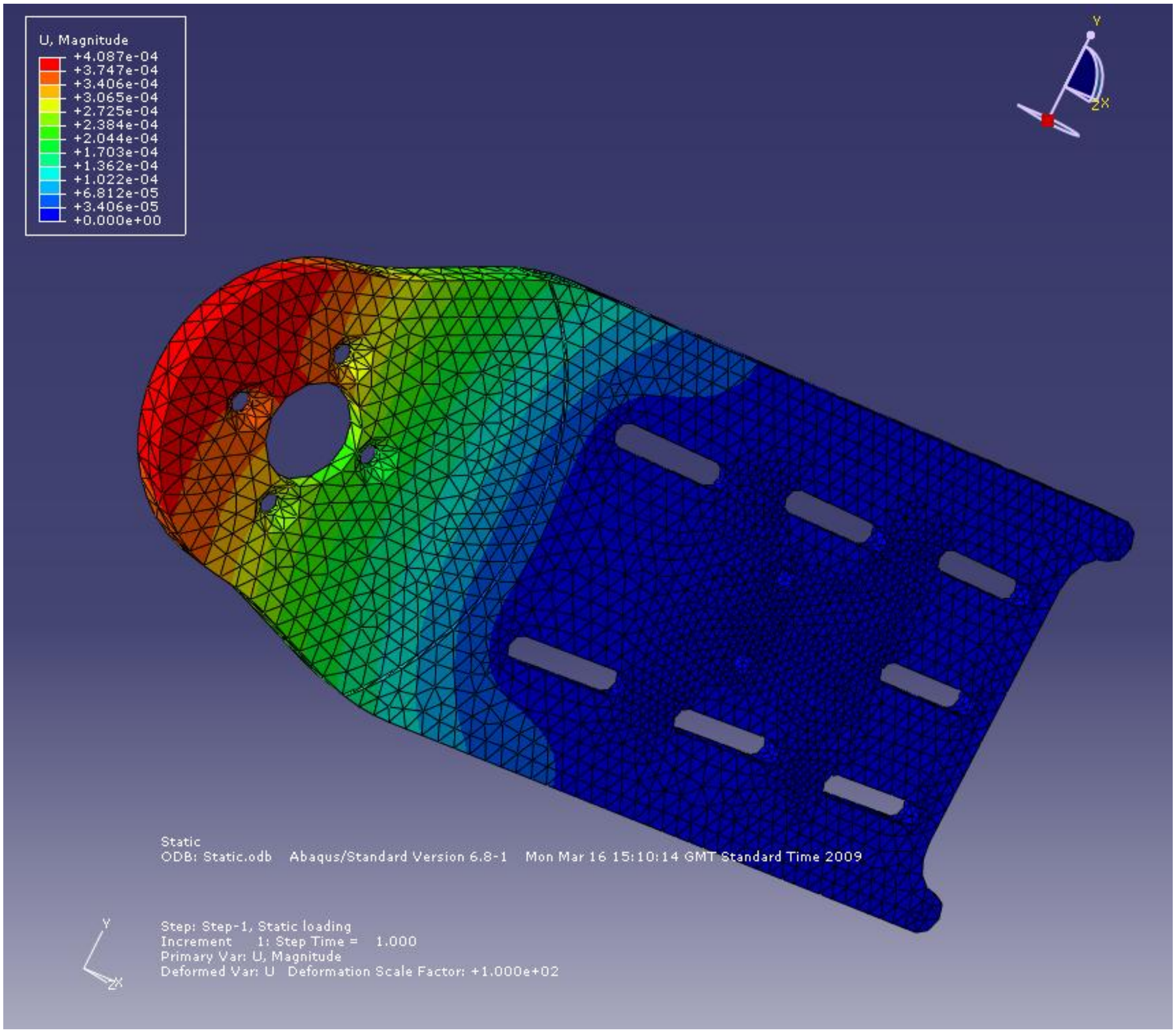


Figure 4-13: Flipper arm plate stress results

A plot of deflection for the static load is shown in Figure 4-13 the red region corresponds to a deflection of 4.087x10^-4 mm deflection. So again for static loading this is well within the acceptable limits with a large factor of safety.

4.3.1.3 Control

The front flippers have a Hall Effect encoder produced by Novotecknik mounted on the motor gearbox output shaft (model RFC 4800-600, Appendix F). This runs from a 5 V dc supply and provides a voltage directly proportional to the shaft angle at its output. The output goes from 5% to 95% of the supply (0.25 V to 4.75 V). There is also dead-zone at the extremities of the rotation (0° and 360°) where minimum and maximum voltages are seen (Figure 4-14, the stroke angle is less than 360°).

The ax500 motor control board used for the front flippers expects a full range voltage from ground to the supply over the rotation range. These limitations mean that a small angle has been defined as a no-go region for the flipper arms.

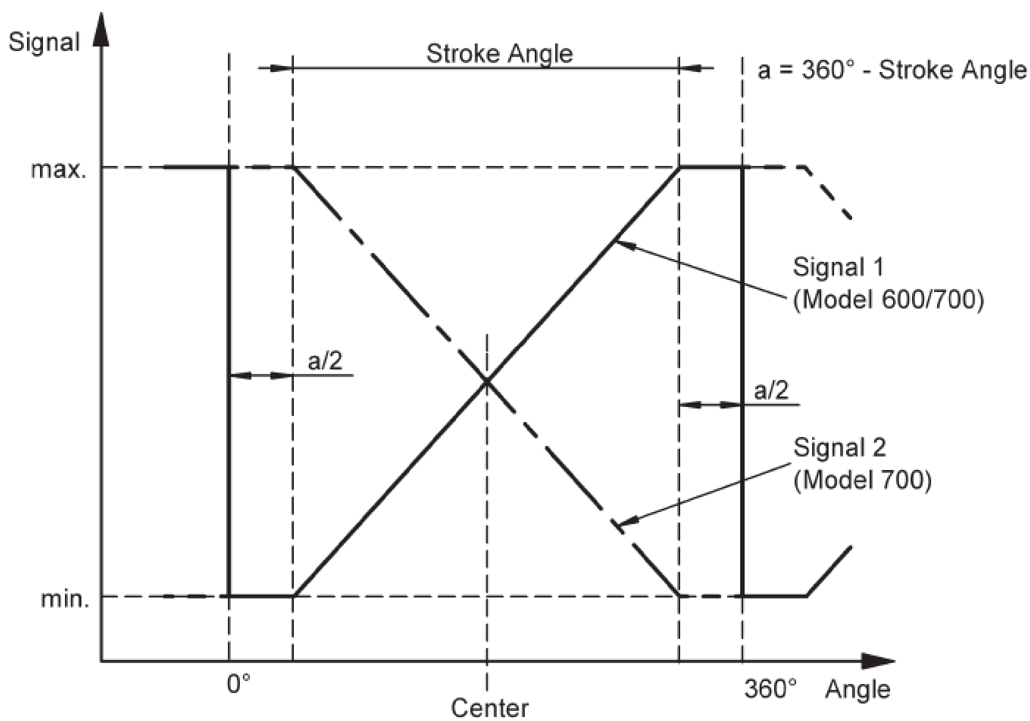


Figure 4-14: Hall encoder characteristics Invalid source specified.

The new rear flipper motor has an optical relative encoder on the motor shaft. This allows full 360° travel when connected to a control board such as the ax3500 as used for the drive motors. An optical encoder sends pulses as the motor turns which are used to increment and decrement a counter. Limitations of this board mean it can only move a maximum number of counts. This corresponds to 15° of movement for the flippers since the motor gearbox has such high reduction ratio. Moving the flippers in steps of this angle, or smaller, is not a problem and can corresponds to a single move flipper command. Using this motor control board means that the work to implement control of the rear flippers should be minimal since the communication routines are already established and closed-loop position control is built into the controller.

With two flipper sets that have overlapping workspaces it is important that at least one set has 360° travel to reduce interference.

4.3.1.4 Flipper Drive

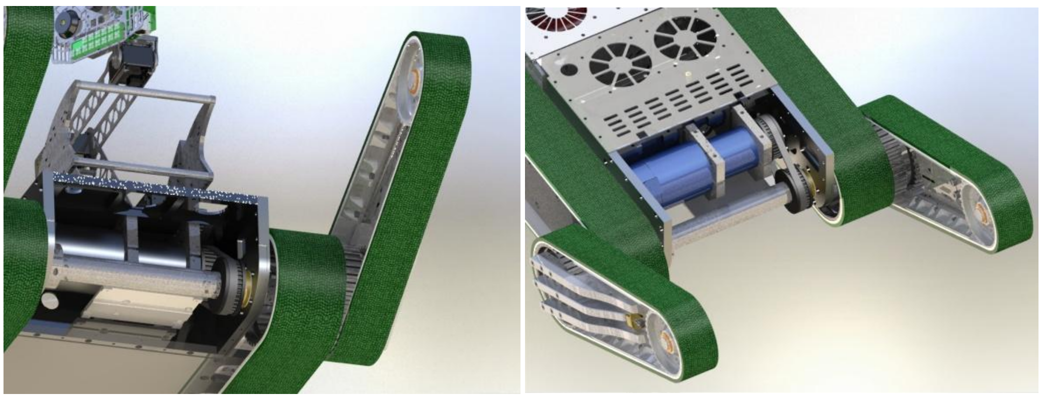


Figure 4-15: Renders of old belt & pulley transmission on flipper drive

The flippers of the 08 robot were driven by a belt and pulleys as shown in above images (Figure 4-15). The belt stripped when high torque was required to lift the robot up onto the flipper arms (Figure 2-2). Belts do have the benefits of not needing any lubrication so are clean and operate quietly. Weaknesses are elastic properties that require the belt to be in tension and the problem of stripping. Using wider belts is a possibility so the load is spread across a larger area and less likely to fail.

As an alternative a direct drive system using meshed gears was considered but the space required is too large for what is available in the front chassis compartment.

The decision was made to use a roller chain and sprockets, overcoming the need for high tension and using materials less likely to strip and fail. Avoiding tensioned belts also makes for a very efficient transmission system over a large range of speeds. The roller chain power transmission system is much better suited to the required operation since it excels at transferring a large load at low speeds, whereas the belt and pulley power transmission is more suited to transferring low loads at higher speeds. Thus the greater strength of the chain compared to the belt and the compact nature of the transmission make the chain drive the obvious replacement to the belt and pulley, Chains are available as single strand (simplex), duplex or triple. A simplex chain was chosen with large pitch since it is more economically. Multistrand chains and sprockets are more expensive and have little power transmission capability benefit over larger pitch single strand chains.

For ease of maintenance and convenience, an identical drive system was chosen for the new rear flipper set.

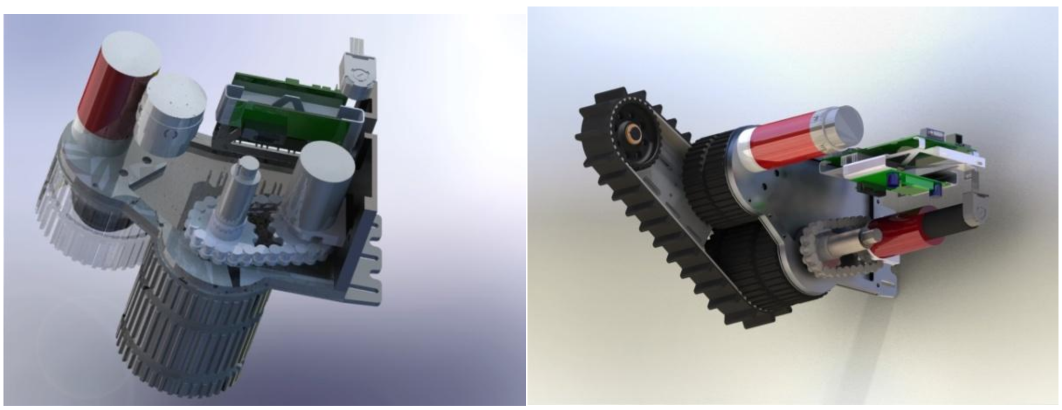


Figure 4-16: Renders of chain & sprocket transmission for rear flipper drive (identical to front flipper drive)

HPC Gears were consulted on specifications and provided with the loading conditions. They then recommended a solution which was purchased.

4.3.1.5 Motor and Encoder Selection

As a primary decision maker the rear flipper motor was desired to be as compact as possible whilst providing sufficient torque to lift the robots weight at a rotational speed comparable to that of the front flippers.

From Figure Figure 4-10 it is shown that the maximum torque required should be around 36Nm. Taking into account a safety factor then assuming 50 Nm is desirable.

Out of both Parvalux and Magmotor could not provide a package that meant the design constraints imposed by the rear chassis.

The supplier Maxon Ltd. was chosen for their small motors and large reduction gearbox combinations (Appendix F).

During testing it was observed that the encoder gearbox combination produced an extremely high output count per shaft turn. The control board can only deal with a finite number of counts and this limited the maximum turn available of the flippers. The result was a maximum turn distance of 15°, comparable to that of the front flippers and so deemed suitable for working with.

Table 4-2: Movable distance from AX3500 control board

counts per motor turn	500
reduction	756
counts per g.box turn	378000
counts per degree	1050
max counts movable	16129
max ° movable	15.36095

4.3.1.6 Chain & Sprocket selection

The motor power and the input speed were the primary properties required for the chain pitch specification. The motor power was identified as 0.059kW and the driving speed of the flipper was said to be 10 rev/min.

These two properties allowed the consultation of the chain drive selection from the British standard chain specification graph (Figure 4-17). This graph had to be extrapolated for the unusually low design power and speed that is not normally experienced in industry.

The intersection of the power and the revolutions per minute of the drive shaft indicated that the ideal chain pitch was ½ inch.

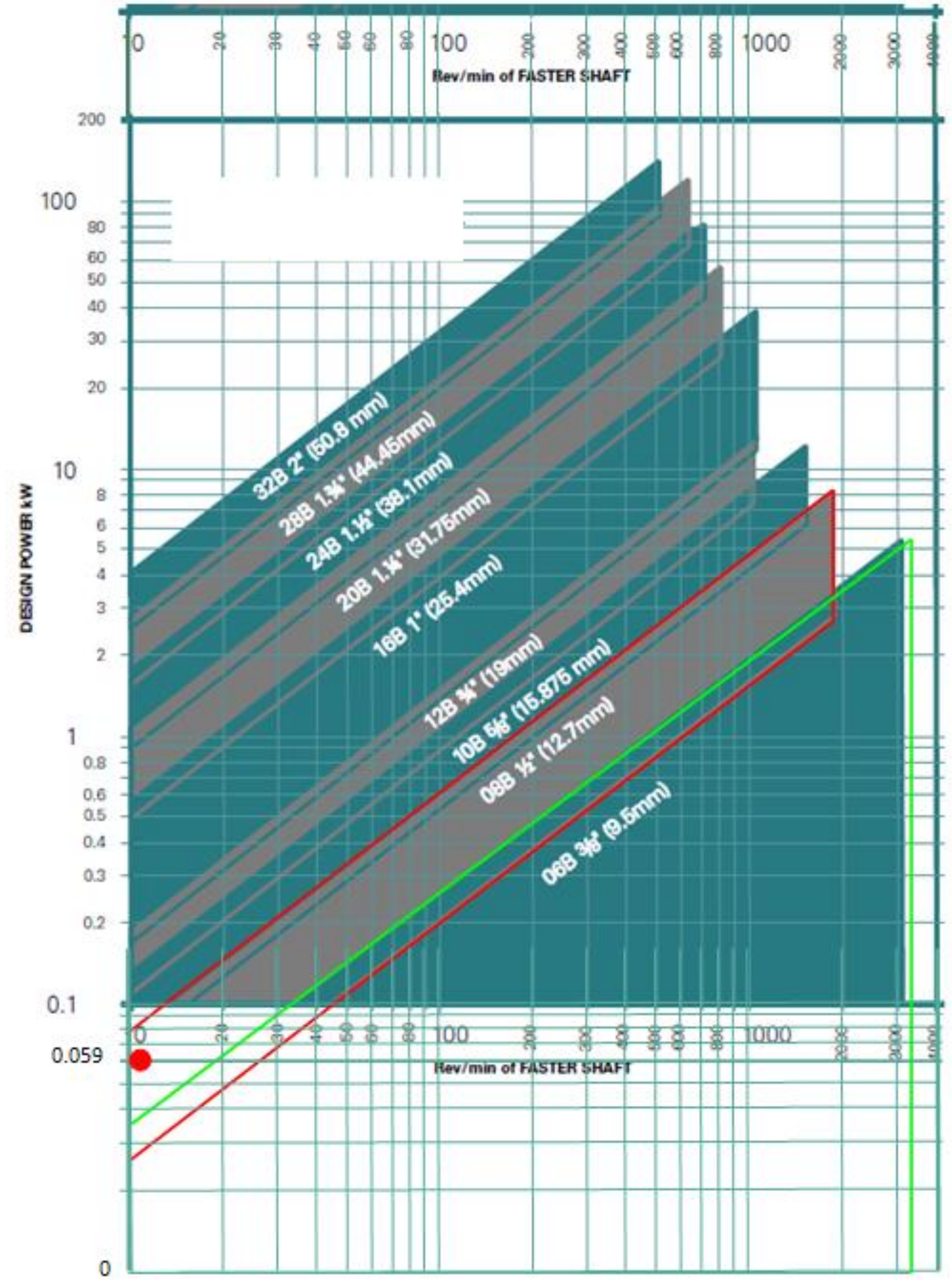


Figure 4-17: British Standard Chain Drive Selection Graph

The red dot represents the intersection of the two values, within the ½ inch pitch region.

The power transmission runs at a 1:1 transmission ratio so there is a 180° wrap angle between the two sprockets and they are spaced with a maximum centre to centre distance of 72 mm due to space restrictions within the chassis.

This centre distance is significantly under the recommended distance of 30 to 50 times the pitch (Figure 4-18), since a larger centre to centre distance would allow the links within the chain to recover between the substantial forces experienced by the chain components when passing over the sprockets.

Chain Pitch	Inches	3/8"	1/2"	5/8"	3/4"	1"	1.1/4"	1.1/2"	1.3/4"	2"
	mm	9.525	12.7	15.875	19.05	25.4	31.75	38.1	44.45	50.8
Centre Distance	mm	450	600	750	900	1000	1200	1350	1500	1700

Figure 4-18: Recommended chain centre distance

This is not seen as a problem since the recommendations are more suited to industrial chains that are expected to run continuously at high loads whereas the flipper drive will only run rarely and intermittently at high torques, but would mostly operated at low torques.

12 tooth sprockets with ½ inch pitch were chosen from the manufacturers (HPC gears) handbook. These were chosen due to their smaller diameters with regards to the limited space within the chassis of the robot.

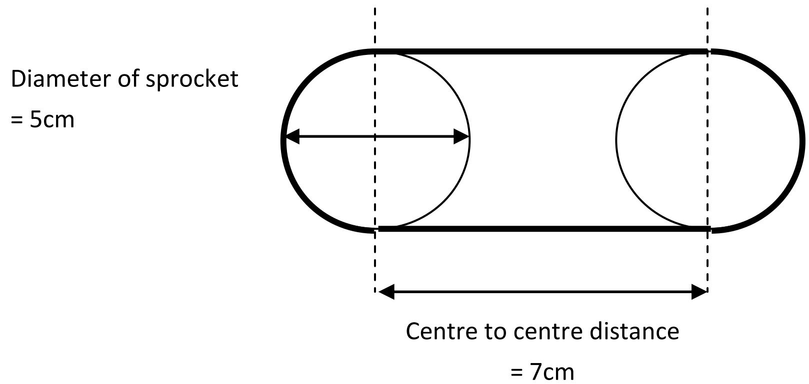


Figure 4-19: Centre to centre distance of sprockets

The pitch circle diameter of the 12 tooth sprockets (part number S50-12) is 49.06mm, a simple calculation was done to find the number of links required in the chain.

$$Length\ of\ chain = 7 + 7 + \pi(5) = 30cm$$

The length of chain required was 30cm long which converts conveniently to about 1 foot, this required 24 links of ½ inch chain to be ordered from the manufacturers HPC gears. Chain and sprocket mounting on flipper motors:

The HPC gears sprockets are delivered as standard with an 18mm diameter internal bore with a 4mm keyway feature. The output shafts of both flipper drive motors are 12mm hardened steel with a 4mm keyway.

In order to provide effective mating and mechanical locking a bush would be required to fill the remaining space.

On the outer face a keyway could be machined. On the inside this would not be possible and so an alternative method of holding would be required. It was chosen to utilise grub screws to provide this locking whilst a traditional key would be used to for the bush to sprocket link.

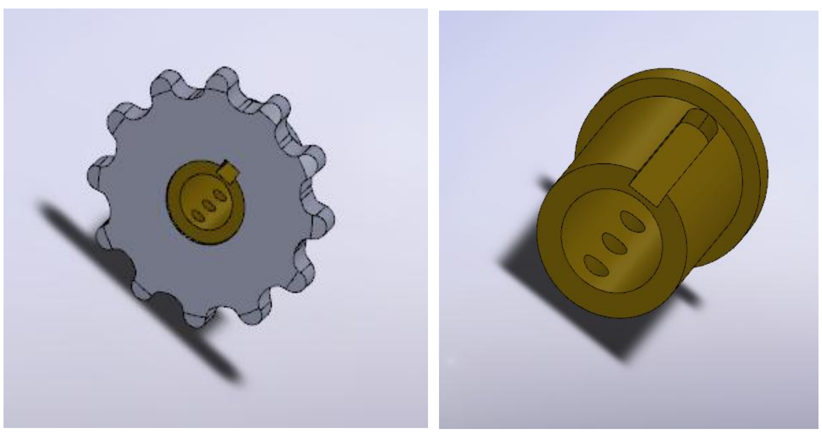


Figure 4-20: Sprocket and bush

4.3.1.7 Flipper Shaft Design

From feedback gained from the 08 team it was apparent that one time consuming aspect of the robot was stripping the flipper assembly to replace broken flipper drive belts. The risk of belts shearing shall be removed through the use of drive chains and sprockets at a 1:1 ratio.

This ratio is desirable as it allows encoders based on the gearbox output shaft to be used to detect flipper position simply and without a scaling factor. A scaling factor could be used for up to 360° rotation of the gearbox output shaft with an absolute encoder (such as the Hall effect unit).

To minimise the spares count it would be preferred to have a paired system for the front and rear flippers.

The design needs to:

- Provide drive to the left and right flippers
- Be quickly and easily removable
- To provide access to housed electronics once removed

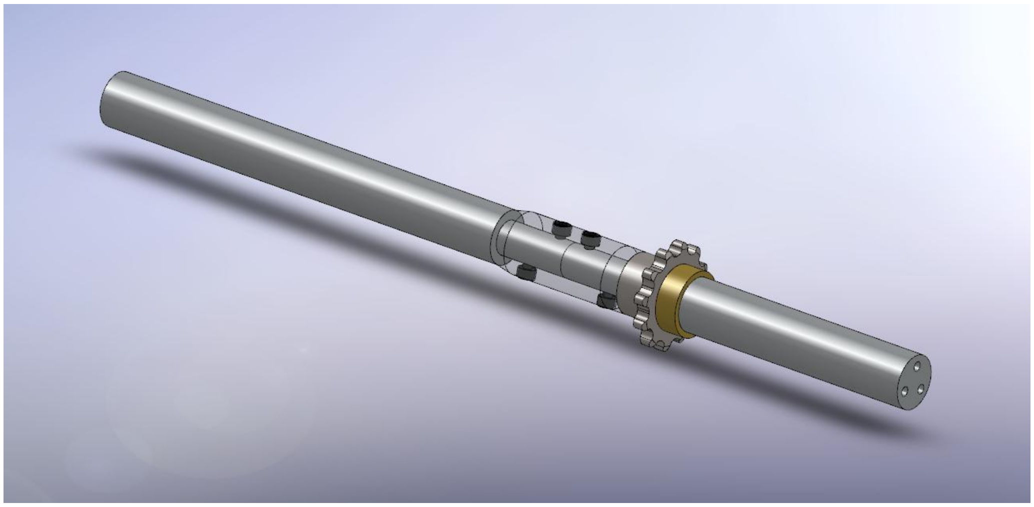


Figure 4-21: Flipper split shaft design

The new design provides a positive mechanical lock through two M5 x 12mm bolts in each shaft with torque transmitted through a clearance fit sliding collar.

A preferred design here would be to have the collar and inserts broached in order to run a keyway down the system allowing for faster removal but due to in house manufacturing restrictions this is not possible.

The main design consideration for the split flipper shaft was that it would provide a similar design for front and rear flipper drive. As the location of the front flipper motor and therefore sprocket where defined the measurements were taken from there.

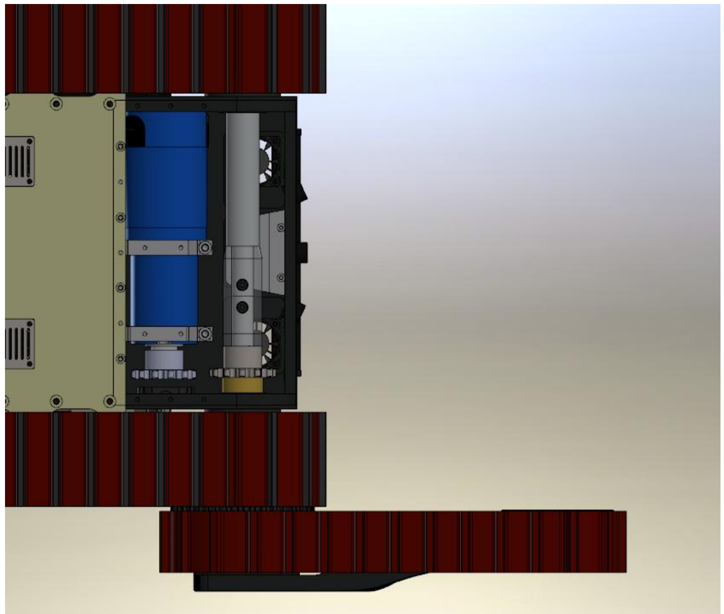


Figure 4-22: Flipper split shaft arrangement

The design must create a shaft extension of 12.3cm from the outside faces of the chassis in order to provide smooth belt running between the compound and flipper pulleys. This defines the shaft length at 49.6cm.

The shaft split is not centred and so the assembly will be sided. This allows a smooth profile to be attained and this shall prevent snagging or rubbing of any front section wiring.

As shown in Figure 4-22, a brass spacer is used to prevent any movement of the shaft along its axis and through the polymer bearings. On the other end of the shaft a 28mm locking collar will be used the same as in the 2008 design. This way sideways movement forces from any impacts cannot be passed onto the motor sprocket imparting deflections onto the gearbox output shaft as this creates a damage risk.

4.4 Power

The robot has no wired link to the base station so operation from batteries is essential. This specifies that DC supply must be used, with a large input voltage range to permit several battery types and also accept the variations between charged and discharged batteries. The power system is also responsible for safety features and including emergency stop functions. (hard E-stop triggered by a button mounted locally on the robot and soft E-stop triggered remotely from the client software).

Table 4-3: Voltage and current requirements

Supply Voltage			
Outputs	24 V	3.5 A	Computer
	12 V	1 A	IR camera, fans, flipper controllers
	5 V	4 A	LiDAR, sonar, webcams, router
	24 V	2 A	LED arrays, fans
	24 V	64 A (typical)	Motors
	18, 15, 12 V	1.5 A each	Arm servo motors

The robot power system

- Shall have minimum run-time of 25 minutes over the competition terrain and should operate for over 2 hours with motors disabled to allow software development
- Shall default to motors off should it lose power (best achieved by powering directly from batteries or mains like the motors)Shall start-up with motors un-powered (hard E-stop)
- Shall release a hard E-stop when the case mounted reset button is pressed
- Shall communicate with the computer
- Shall accept computer command to trigger soft E-stop (turn-off motors)
- Shall release a soft E-stop when an appropriate computer command is received
- Shall enter the hard E-stop state when the red emergency stop button is pressed
- Shall enter the soft E-stop state if a computer "heartbeat" signal is missed (a watchdog indicating that the computer is down so the robot should stop)
- Shall run from mains or batteries and shall switch between the two without powering down the robot and mains should take precedent

- Shall provide constant voltage outputs as given above with the appropriate current rating
- Shall provide sufficient cooling for the power dissipation of the components
- Shall provide power cycling for all outputs (computer command to power down and back on any output)
- Should have separate outputs for each sub-system (eg. Cameras and LiDAR)
- Should have appropriately rated fuses on all outputs

4.4.1 Batteries

The 2008 competition robot used twenty Ansmann D-type Nickel Metal-Hydride cells (NiMH). These were mounted in a pack of ten on either side of the robot to give two 12 V batteries connected in series for 24 V. The typical power consumption is 346 W(9)which gives a run time of 41 minutes. With use since the competition the useful run-time from these batteries has decreased to around 25 minutes.

Another drawback with these batteries is the voltage drop when working at maximum load. Shown in Figure 4-23 is the battery voltage and current at motor stall conditions (when the robot is driving into a solid obstacle with downforce applied so the motors are prevented from turning). The voltage drops to 13 V which threatens to reach the drop-out voltage of many electronic systems including the computer. With weak batteries this does occur. Alternative power sources were sought that gave comparable overall operation but did not suffer as much from degradation over time or drop voltage at high current, thus allowing the motors to operate at their full capability.

An option was to use lithium-ion (Li-Ion) cells from A123 Systems Inc. (ANR26650M1). These cells have desirable current-voltage curves but the low cell capacity and high cost made them prohibitive. The pack size would need to increase and each set would cost USD 789.

The chosen option was lithium-polymer (LiPo) batteries. These can be purchased as pre-assembled batteries designed for use in model helicopters. The Flightpower Evolite 5350 mAh battery has six 3.7 V cells in series to give 22.2 V.

The same stall testing was performed for the LiPo batteries. They can provide maximum continuous current of 91 A and maximum burst of 150 A. This compares to 50 A maximum for the NiMH batteries. Figure 4-24 shows the results of this loading. The peak current is over 40 A (only 27 A for NiMH) and the voltage drops by only 3 V. This overcomes the drop-out problem and also allows the drive motors to run to their full potential.

The final decision was to use two LiPo batteries in parallel to achive the same capacity as the old NiMH batteries. The small reduction in voltage does not affect the operation of other systems.

A SWOT analysis is provided in Appendix A.

Table 4-4: NiMH Batteries

Type	**NiMH (Nickel Metal-Hydride)**	
Capacity	10 Ah (cell)	10 Ah (pack)
Voltage	1.2 V (cell)	12 V (pack)
Dimensions	33 mm (diameter)	61.5 mm (height)
Mass	155 g (cell)	1.5 kg (pack without mounting)
Cost	£9.45 for <24 (order in quantities of 2)	
	Each battery set costs £189	

Table 4-5: LiPo Batteries

Type	**LiPo (Lithium Polymer)**		
Capacity	5.35 Ah (cell)	5.35 Ah (pack)	
Voltage	3.7 V (battery)		
Dimensions	144 mm (length)	43 mm (height)	63 mm (depth)
Mass	699 g (battery)		
Cost	£164		
	Each battery set costs £328		

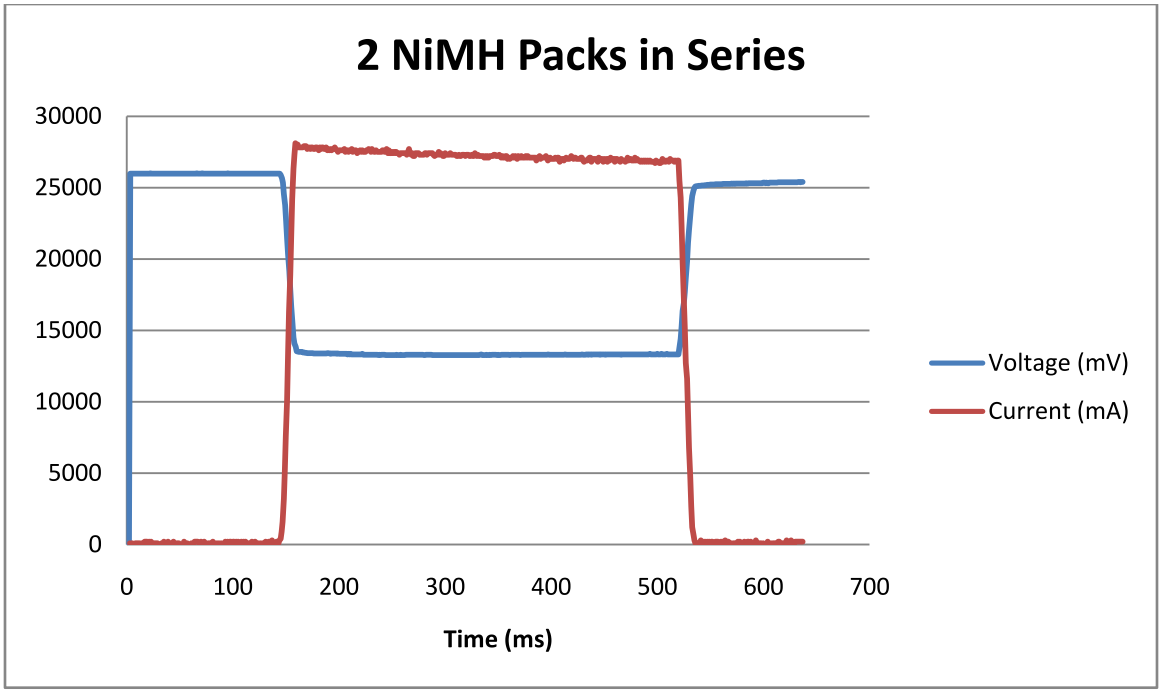


Figure 4-23: NiMH loading with fully charged batteries (two packs)

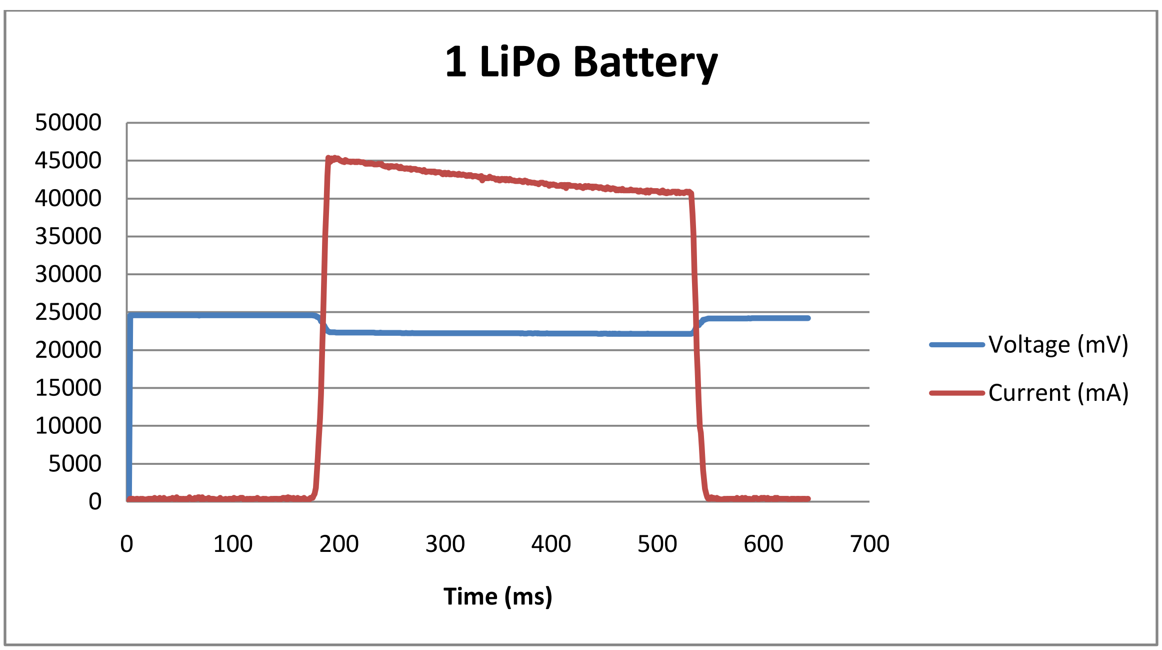


Figure 4-24: LiPo loading of fully charge battery (one battery)

4.4.1.1 Wiring

To maximise the ability to operate the robot, the new battery enclosures were designed to mount to the robot chassis in the same way as the NiMH enclosures. However since the NiMH batteries are wired in series and the LiPo batteries in parallel the connections to the robot internal power system had to be considered. The wiring shown in Figure 4-25 allows the 12 V NiMH packs to work in series and the 22.2 V LiPo packs to work in parallel. Matching the coloured connections on the packs and robot ensure the batteries are properly connected.

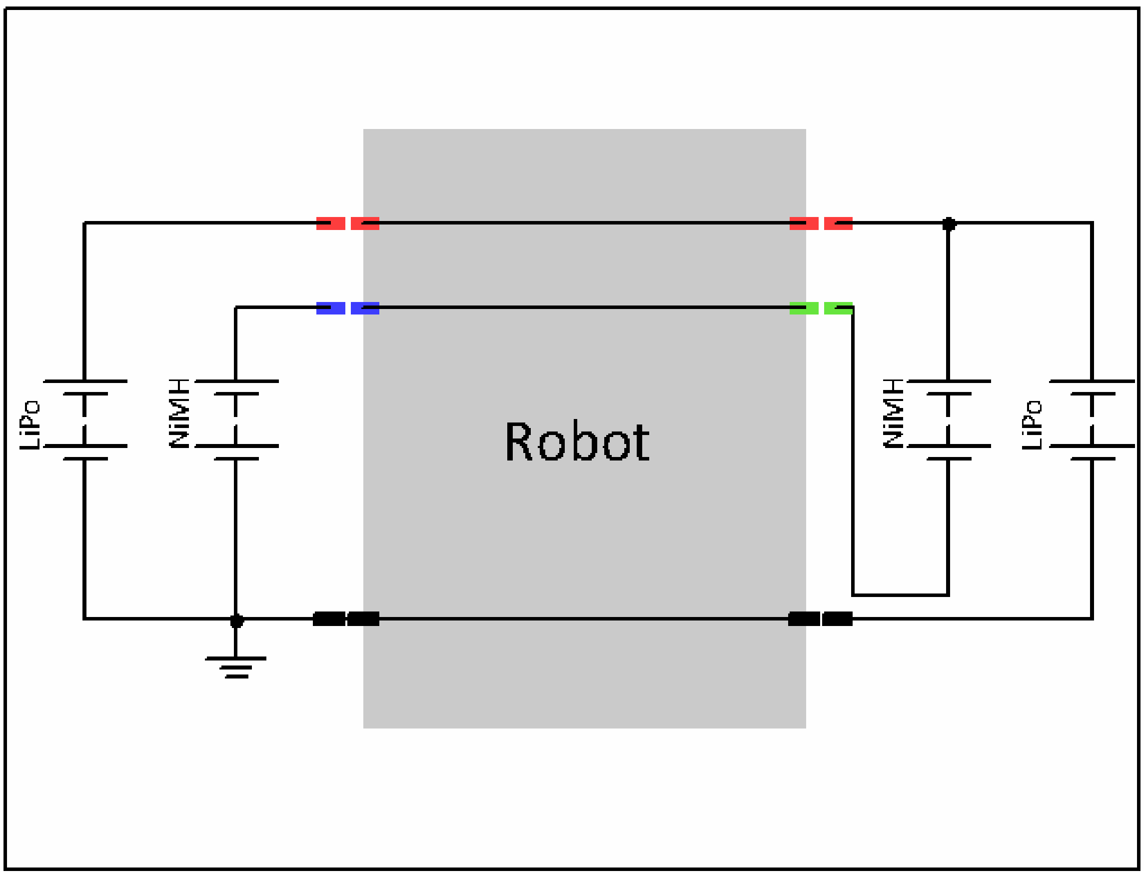


Figure 4-25: Wiring diagram

Power poles are used for the battery connections. These are individual connectors capable of carrying 75 A which was found to be above the maximum drawn by the motors (Figure 4-24) from a single battery. They also connect together side-by-side. Inserts are crimped onto the wires, rather than using the screw terminals that frequently disconnected on the 2008 robot. Power poles also link the front, centre and rear sections of the robot for delivering power to the motors.

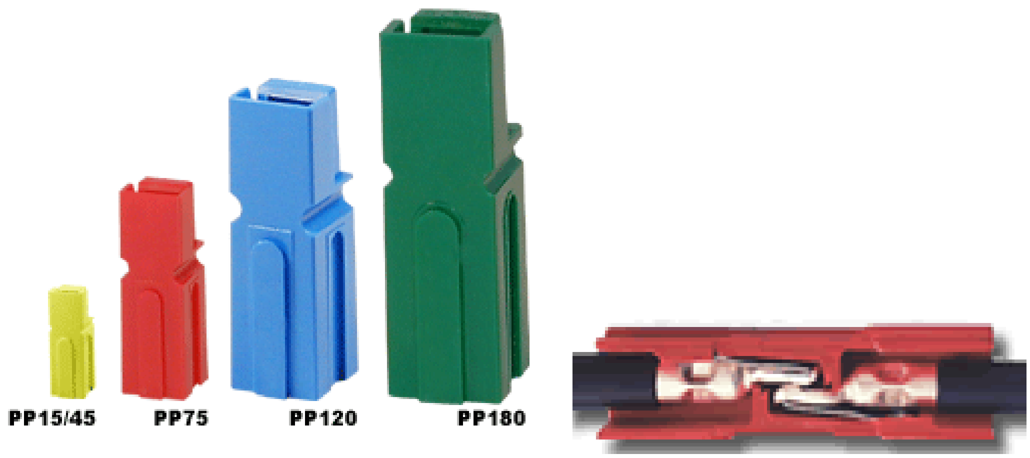


Figure 4-26: Power poles and mating(10)

4.4.1.2 Battery Enclosures

Utilising the prior experience of WMR, it is known that physical damage, such as piercing, to LiPo batteries can cause violent explosion. LiPo batteries are used in the WMR Evolution robot footballers(11). A protective housing is required to prevent knocks during operation. The design of this enclosure is detailed in Section 4.4.1.2.

4.4.1.3 Charging

The Robbe 12 V battery charger used for the NiMH batteries can be configured for LiPo batteries. However LiPo batteries require an additional equaliser unit to ensure the individual cells charge equally. This is to prevent uneven charging causing an individual cell to discharge beyond the safe minimum of 3.0 V, while the total battery voltage is still within operating limits. Taking LiPo cells outside their safe range is not recommended. Damage may be caused which could be dangerous (risk of explosion) when recharging.

From experience the LiPo batteries maintain their voltage until they become very close to fully discharged making it difficult to determine when they are running low. To prevent over-discharge damage the battery voltage should be monitored and the robot should shutdown when it gets low.

For safety, protective bags are used while charging. These LiPo sacks are designed to contain a LiPo explosion.

4.4.2 Power Distribution Board

The power distribution and control board is responsible for regulating all the lower voltage outputs and implementing the emergency stop of the drive and flipper motors.

Some of the 2008 design has been retained, including the simplified mains and battery switching circuit using two diodes. This gives mains the priority if it is higher voltage (27 V supply is used) since the battery diode is reverse biased.

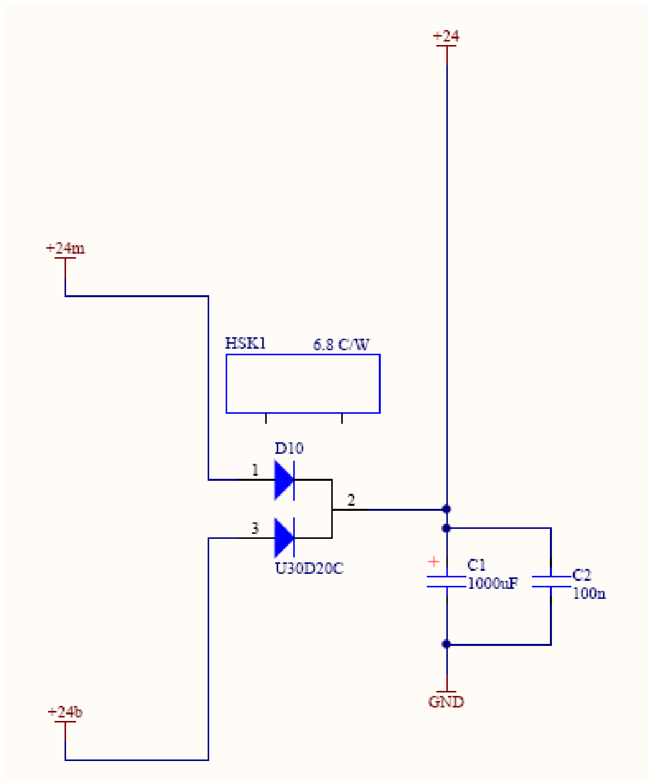


Figure 4-27: MOSFET Switching Circuit (24b from batteries and 24m from mains)

The primary motivation for development of a new power control board was that the power cycling and soft E-stop functionality was not fully implemented. The old board was also damaged by a chassis ground fault (Section 4.4.3 Temporary Power Board).

The board also forms part of the removable central section as detailed in Section 4.5 which constrains the physical size to 165 mm by 220 mm. As part of this unit, it was practical to design a single board which combines the voltage regulation and switching functions of the two circuit boards used in the 2008 robot. Surface mount devices (SMD) were chosen where possible to more easily fit the electronics into this area. A circuit diagram and PCB layout is shown in Appendix A.

4.4.2.1 *Voltage Regulation*

With an input between 20 and 30 V the board needed to supply all electronic subsystems at lower voltages. The 2008 power board used LM2576T switching regulators that use many external components, including large through-hole inductors. Integrated DC-DC converters were selected instead which provide a drop-in solution.

Figure 4-28: Tracopower regulators(12)

The TEL 30 series were selected at 5, 12 and 15 V. They offer 30 W outputs which provide sufficient current at each voltage for the electronic devices in Table 4-3.

The computer, lighting and fans can operate directly from the battery supply (or mains). The motors are also powered directly from the batteries without passing through the power board due to the high current. A mechanical relay is used for switching.

In addition, the robot arm ideally uses an 18 V supply. No integrated converter could be found at this voltage so a circuit was constructed around a MAX1745 adjustable DC-DC converter. The calculations for the external components are available in Appendix A.

Table 4-6: Voltage for electronic devices

Electronic Device	Voltage	On battery	On mains	Switchable
PC	24 V	Yes	Yes	-
Router	5 V	Yes	Yes	Yes
Motors	24 V	Yes	-	Yes (E-Stop)
Central fans	24 V	Yes	Yes	-
IR Camera	12 V	Yes	Yes	Yes
Webcams	5 V	Yes	Yes	Yes
LiDAR	5 V	Yes	Yes	Yes
Compass	5 V	Yes	Yes	Yes
RX64 (arm base/elbow)	18 V	Yes	-	Yes (and E-stop)
RX10 (arm wrist)	12 V	Yes	Yes	Yes (no E-stop)
RX28 (spare servo)	15 V	Yes	Yes	Yes (no E-stop)
Front fans	12 V	Yes	Yes	-
Front LEDs	24 V	Yes	-	Yes
Arm LEDs	24 V	Yes	-	Yes
Flipper controller	12 V	Yes	Yes	Yes
Drive and rear flipper controller	24 V	Yes	-	Yes

4.4.2.2 Emergency Stop Motor Control

The power board is to provide the means to remotely stop the motors and also interact with a local hardware E-stop mounted on the robot lid. For any robot with moving parts safety is a very important factor to consider.

The hardware components of the safety system are the red emergency stop button (which latches in either state), a reset button and two relays.

Referring to Figure 4-29, switch J1A represents the emergency stop button and button S1 is the reset. This circuit was simulated to test functionality. Relays K1 is found on the power board. Switch J2 and relay K3 make up an electronic switch produced with a MOSFET and microcontroller output to give software E-stop capability.

On start-up the reset button must be pressed with the emergency stop released before the robot can move. The reset activates relay K1 which then activates relay K2 providing the software E-stop is not activated. K2 is a large high current relay in series with the motors (represented by the LED). Pressing the emergency stop deactivates all relays and the button must be released and reset pressed to restart. The software E-stop can be toggled without requiring the reset button to be pressed giving remote emergency stop functionality.

The safety circuit worked from a hardware point of view in the 2008 robot. The software E-stop was not fully implemented. The only hardware change is to use MOSFETs to toggle the software E-stop rather than a mechanical relay. The use of solid-state devices should prolong the lifetime of the system and introduces less noise on the microcontroller signal lines.

Since the E-stop relay always starts up in the open configuration, the robot is initially in the first or third state and a button on the robot must be pressed to activate the relay before the motors are powered. The operator pressing this button can ensure safety by checking the area around the robot is clear of other people. In the table below the bold lines indicate actions that result in active motors.

Table 4-7: Emergency stop sequence and states

Current Condition	E-stop State	Reset State	Resulting Condition	Notes
Motors off	0	0	Motors off	motors will not start whilst E-stop is pushed in
Motors off	0	1	Motors off	motors will not start whilst E-stop is pushed in
Motors off	1	0	Motors off	system ready and waiting for reset to be pushed
Motors off	**1**	**1**	**Motors on**	**E-stop ready; pressing reset starts motors**
Motors on	0	0	Motors off	pressing E-stop cuts power
Motors on	0	1	Motors off	E-stop has been pressed, motors cannot start
Motors on	**1**	**0**	**Motors on**	**motors are already running, the state of reset does not matter**
Motors on	**1**	**1**	**Motors on**	**motors are already running, the state of reset does not matter**

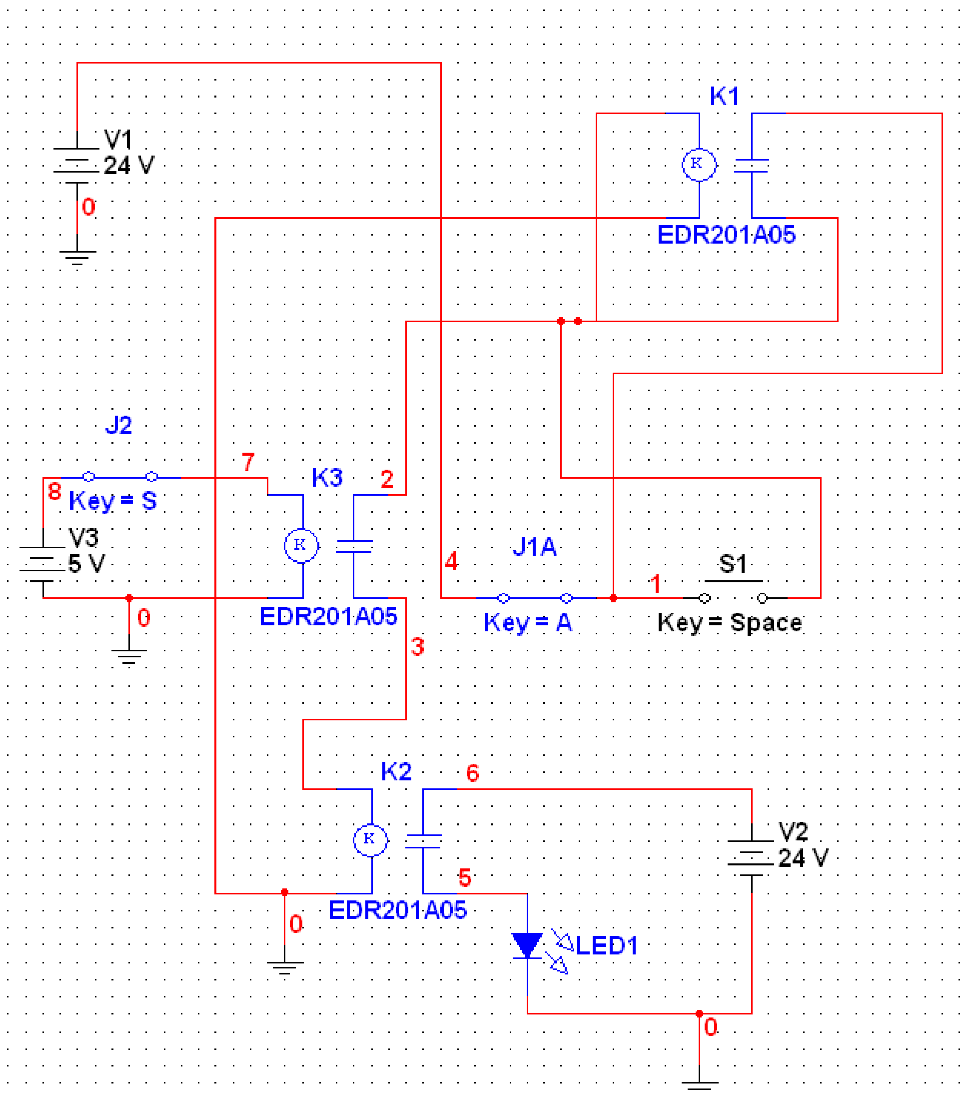


Figure 4-29: Emergency stop circuit

4.4.2.3 Cooling

All DC-DC converters are switch type so have minimal power dissipation. They are metal cased and the board is located under fans in the central section lid. The power supply selection diode does carry high current so it has a heat-sink rated at 5 K W^{-1}. This is the same heat-sink as used on the 2008 board and calculations for required heat dissipation are found in the WMR 2008 Hardware Technical Report (9).

4.4.2.4 Microcontrollers

Two microcontrollers are used. Both are Atmel ATmega64-16AU devices available in 64 pin TQFP package. These microcontrollers were used on the 2008 board also on the robot footballers so transferrable source code is available.

One microcontroller listens for a heartbeat signal from the on robot PC, activating a software E-stop if communication with the PC fails. It also listens for a software E-stop command.

The other microcontroller is connected to the output switching circuitry and listens for commands to switch-off or turn-on each output channel on the power board.

4.4.2.5 Output switching

To implement output switching a pair of MOSFETs were used. An n-channel device with its gate connected to a 5 V signal from the microcontroller and a p-channel device to switch the high voltage supply.

This circuit will be tested after construction of the power board but works in simulation.

SMD fuses are placed on the outputs and LEDs indicate output state.

4.4.2.6 Communication

The microcontrollers have built in TTL level (5 V) communication ports using the RS232 protocol. For communicating with a PC it is more convenient to use the Universal Serial Bus (USB). A serial-to-USB converter could be built easily on the board using the FT2232L UART chip which worked in the 2008 design.

The safety and power controllers respond to ASCII characters sent from the computer to switch outputs (see Appendix B for details). It also responds to confirm that the command has been actioned. With no communication (either a command or a special heartbeat character) the software E-stop is activated after approximately 200 ms.

4.4.2.7 Printed Circuit Board Layout

As per the design methodology, Altium Designer was used for schematic capture and PCB layout. Care was taken to ensure track widths were sufficient for the current they would carry.

The connectors for all electronic devices were grouped to one side of the board and a slot cut-out in the side allows wires to reach lower into the robot central stack.

The decision was made to use a commercial PCB manufacturer rather than use the in-house facilities at the University of Warwick since the exposed copper on the 2008 PCB made soldering difficult, especially the surface-mount devices (SMD), and was prone to unintentional short circuits. A commercial board would be covered in insulating solder resist. It also has the advantage of being through-hole plated so populating the board is much easier.

Since considerable funds would be spent on this PCB the layout was verified by creating a cardboard prototype and laying out components to check for height and fit inside the integrated central computer compartment.

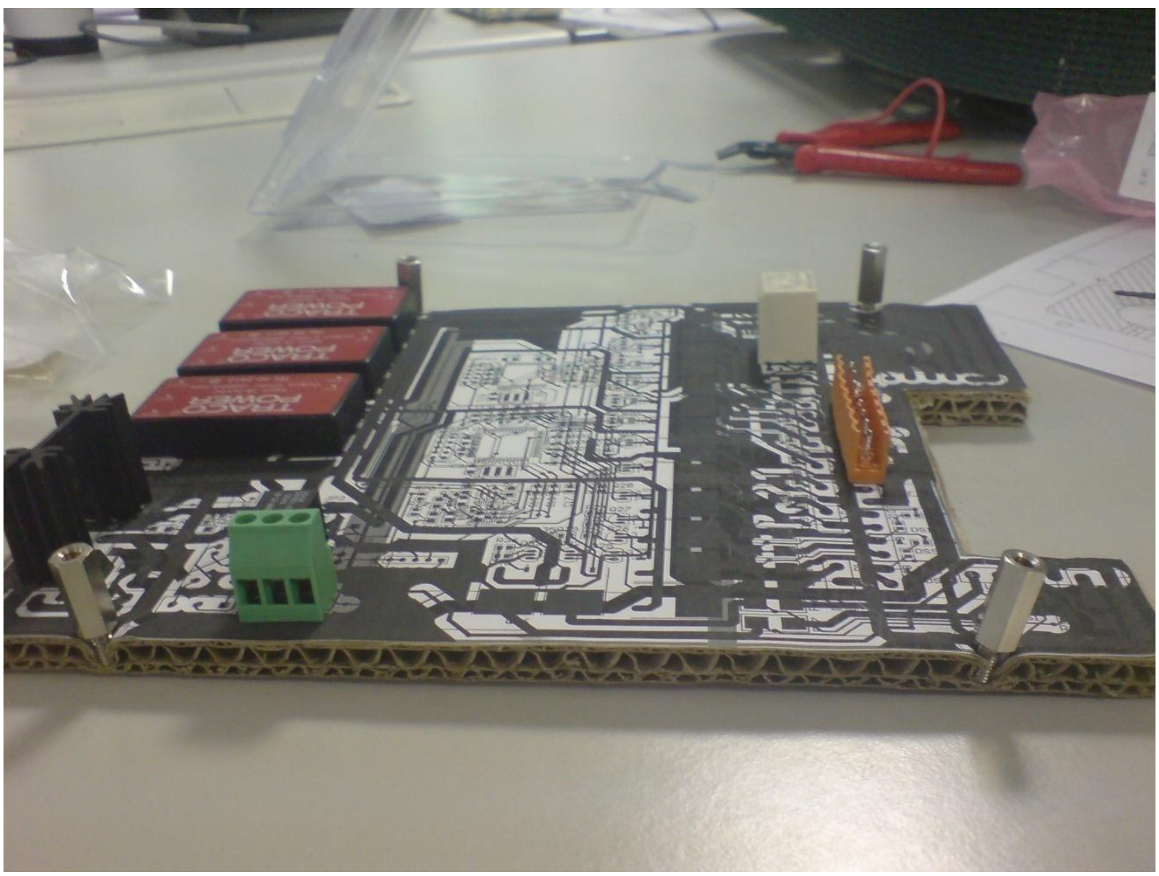


Figure 4-30: Power board layout

4.4.3 Temporary Power Board

To allow development and testing before production of the new board, the old power board was modified to use fixed voltage regulators at 5 V and 12 V. This temporary solution had no power cycling of the output channels and no software E-stop so it was imperative that someone followed the robot and stayed close to the physical emergency stop button.

With no software E-stop capability this set-up was not suitable for long term operation and also did not provide the correct arm servo voltages so the arm would not work to its full potential.

4.4.4 Polymer parts for weight saving

In order to maintain, as closely as possible, the current weight of the robot, weight reduction of newly designed and manufactured parts will be key in the design procedure. To this end, new lighter weight materials will be used wherever their use shall not hinder the performance or functionality of the robot.

Maintaining similar weight is imperative for the power requirements calculations to be valid since a more massive robot will use more energy moving around the arena.

The properties of nylon, acetal and aluminium are given in Appendix A. There are several additional benefits of polymer parts.

In the past, battery wires have become frayed and the insulating coating has split. This was the reason behind the damage to a power control board, where the battery wire became unsheathed and made contact with the aluminium pulleys. This shorted the batteries through the chassis, passing high current through the power control board, burning out a copper ground track and damaging other components. The use of acetal pulleys provides a safeguard against this fault.

It would not be acceptable to have acetal pulleys as the only preventative measure against this fault and so new battery compartments will be designed with a higher level of compartmentalisation and protection for the power connections and fuses.

The acetal battery casing demonstrates a weight saving over the previous year's design. Even though the cases are larger, the weight saving from the battery change to LiPo units leads to an overall saving for the battery packs.

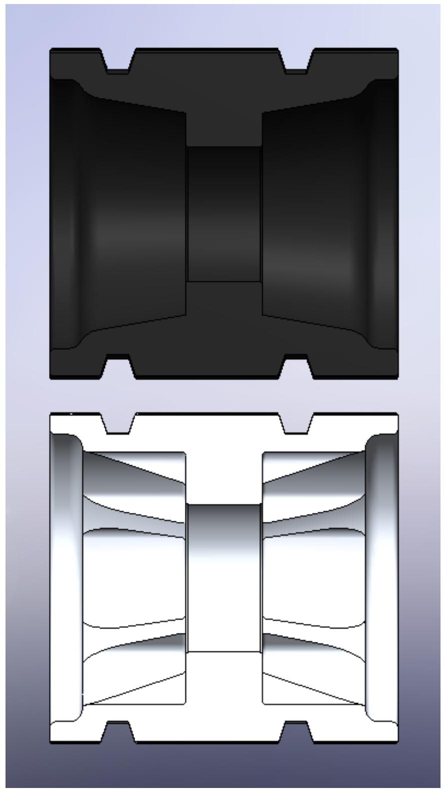


Figure 4-31: Comparison of Acetal (top) and Aluminium (bottom) compound pulley design

Acetal demonstrates a considerably lower specific gravity than aluminium, around 1.4 compared to 2.7. However consideration has to be given to the reduced strength of the material and so the internal profile was made larger. Overall a 30% weight saving was achieved for each compound pulley (Appendix A).

Acetal flipper arms where created for the new shorter designs and a weight reduction per unit of around 50%. This was however offset by the addition of the rear flippers. The level of rigidity of the flipper arm plates shall be lower than that of the aluminium parts although from computer testing (Figure 4-13) it is deemed acceptable

4.5 Central Computer

To keep the 2009 robot as easy as possible to develop and test with various subsystems present and connected the decision was made to develop a removable central compartment for the robot. This subsystem would include the motherboard, hard drive and power board along with other components housed in this section of the robot. This central section increases the compliance of the robot to the particular requirement that each subsystem is a self contained module and is individually testable. In developing the central computer case the central lid was required to be re-designed to allow for extra space to be provided and also to allow a secure mounting point for the whole section to be hung from.

The lid will be machined from black acetal copolymer as it demonstrates a high level of rigidity for a low weight and is easy to machine. The manufacture of this part shall require several machining steps and so an increased rate of machining when loaded will help reduce part cost. This section will accommodate cooling fans, a recess for the robot arm and connection points for external power, communication points (Ethernet, USB and VGA ports) as well as connection to the arm and router aerial. The central compartment will allow airflow through the module to lower chances of components overheating and will also have some shock protection in the form of rubber washers between the lid and the connection to the lid. There were two major designs considered, first a computer case attached to the bottom plate of the central section and secondly a computer case system mounted from the lid which would facilitate the use of springs and dampers for an added level of impact protection for the computer equipment.

The lid design (Appendix A for design drawings) will allow easy connections to the various other subsystems and to permit access to the central computer for a monitor, keyboard and Ethernet for use in debugging of the robot. Along with these connections there will be a cut for the router aerial and also data connections between the arm and the lid and the rear section and the lid. Power connection between the rear and central section will also run through the lid with the use of PowerPoles (Section 4.4.1.1). The central electronic stack will house a number of components including the power control board and motherboard; these will be integral structural members of the case along with a laser cut mounting plate for the other electrical components to be housed in this section. The plate will be cut with holes to allow airflow through the central section and also to reduce weight as much as possible without losing the structural integrity of the casing. The lid must also house E-stop and reset buttons for the robot and computer, these will be flush if possible (reset and computer power button). The E-stop button must be proud to allow the E-stop to be easily engaged, however, the whole button is slightly recessed into the lid to keep the likelihood of accidental engagement low.

To encourage airflow throughout the central section 4 x40 mm computer fans will be placed in the lid which bring air into the central section and 2 x 40 mm fans will be placed at the bottom of the central section to encourage air flow out of the central section. This should keep all component temperatures at a reasonable operating level.

The mounting plate will hold many of the electrical components in the robot, these include the flipper motor control board for the front flippers, the router and the hard drive for the computer. The router will be housed inside a mounting 'cage' of stainless steel (Figure 4-32), this cage will have mounting points for a digital compass or inertial measurement unit (IMU). The central section will be screwed from the bottom into the lid via M4 spacer bolts and will allow the whole computer stack to be lifted from the central section without risk of damage to any components.

Final pictures of the central section mounted in the chassis and out are shown for information.

It should be noted that due to the size constraints of this compartment already given by the 2008 design, the major design decisions were based around fitting the compartment into the given space. This leads to very little flexibility in the size and positioning of the central section.

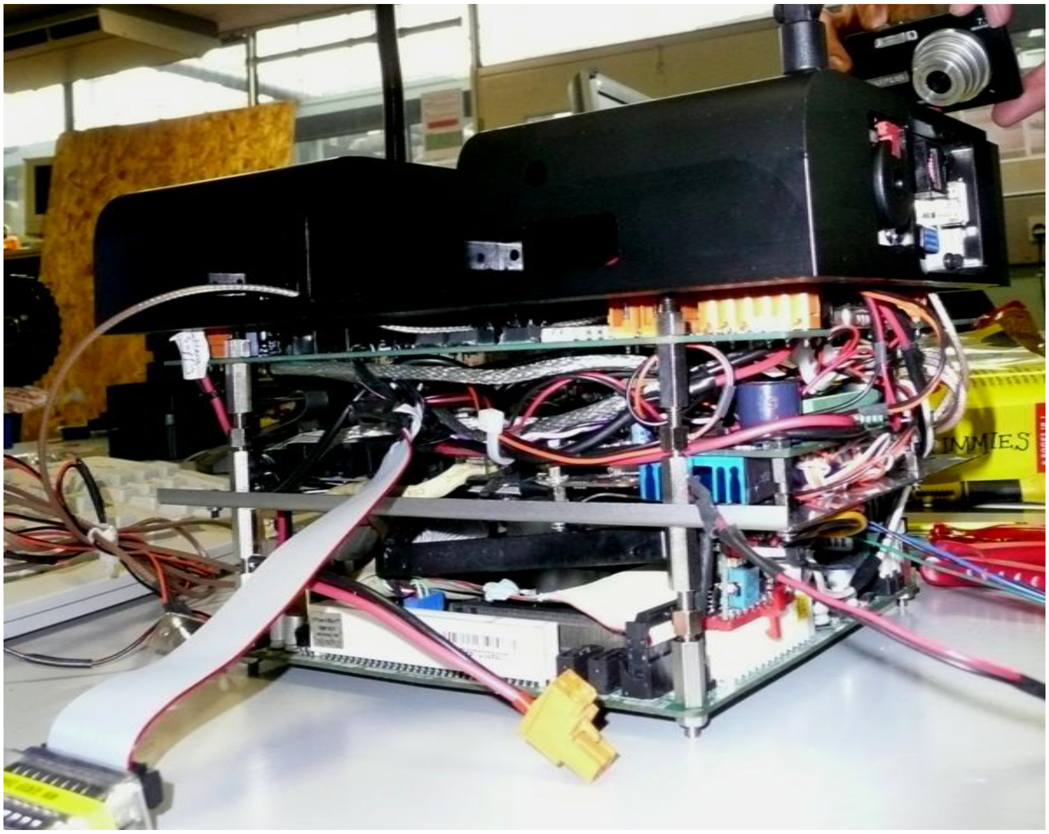


Figure 4-32: Central computer frame outside of the chassis

Figure 4-33: Central computer case mounted in the chassis

4.6 Victim Identification

4.6.1 Tele-Operation

4.6.1.1 Webcams

Webcams allow the operator to see the robots surroundings and easily determine victims through shape and movement.

4.6.1.2 Infra-Red

The infra-red camera allows the operator to see the heat emanating from victims or other warm objects. Unlike the webcams the IR camera can spot heat from a victim that has been partially buried.

The IR camera being used outputs its data using composite video. To capture this data the computer uses a TV tuner and a frame-grabber written in C++ which takes a snapshot of the tuner and inputs it into the JAVA software.

4.6.1.3 Microphone

Microphones onboard the robot allows the operator to listen for any signs of life from nearby victims.

To use the microphones onboard the webcams the server software would have to interpret the video stream from the camera and extract the audio so that I could be sent to the operator. As a short-term fix the audio can be received by the operator through an internet browser and navigating directly onto the cameras web-server.

4.6.1.4 Carbon-Dioxide

Measuring carbon-dioxide is another way in which to find victims as their breath contains elevated concentrations when compared with the ambient values. However, identifying a victim through carbon-dioxide requires the robot to be very close to the victim.

Interfacing with the carbon-dioxide sensor is not a problem as there is a spare channel on the Phidgit board which also interfaces with all of the sonar modules.

Figure 4-34: CO_2 sensor

4.6.2 Autonomous Operation

Searching for the heat spots of potential victims was identified as a good method of autonomous victim identification. The approach decided on was to use the infrared camera with a greyscale output and a fixed temperature colour-mapping. The output of this can then be captured and read by the AI java code for image processing. The first stage of this processing is to run a threshold over the greyscale image to create a binary image. The threshold value represents the temperature above which to search for (roughly equivalent to body heat). This binary image is then analysed and scanned for blobs. The algorithm will then return the number of blobs found, their size and location on the image. This will allow the sensor head to track a target blob.

4.6.2.1 Loading, formatting & thresholding the image

1. First an image is grabbed from the IR camera input feed & converted to pure greyscale if not already in the format.
2. The image is then converted into a binary (black and white) format to extract the relevant temperature range. This is done by scanning through the greyscale image and copying all pixels within a threshold range into a new empty image.
3. This binary image is then passed to a blob detection algorithm.

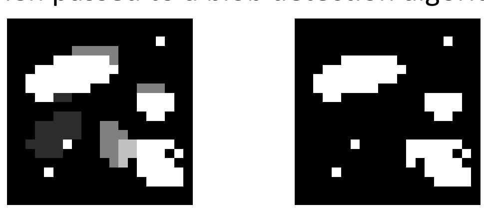


Figure 4-35: Sample greyscale image (left) and result of thresholding algorithm (right)

4.6.2.2 Blob detection and classification

The first implementation of the blob filling software was a purely recursive algorithm:

1. The algorithm works by scanning through the binary image from left to right, top to bottom until it finds a ‘hot’ (white) pixel.
2. When it does, it classifies the pixel as part of a new blob in a separate array containing all blob ID information.
3. It then scans the eight directly neighbouring pixels, checking if they are ‘hot’.
4. If so, they are given the same blob ID number, the blob size is incremented and the function calls itself (recurses) to scan the surrounding pixels of the new pixel.
5. This process repeats until all pixels in a blob are classified, then the algorithm continues scanning left to right, top to bottom for the next blob.

```
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 2 2 2 2 2 2 0 0 0 0 0 0 0 0 0
0 0 0 2 2 2 2 2 2 2 2 2 0 0 0 0 0 0 0 0
0 0 2 2 2 2 2 2 2 2 2 0 0 0 0 0 0 0 0 0
0 0 2 2 2 2 2 2 2 0 0 0 0 0 0 0 0 0 0 0
0 0 0 2 2 0 0 0 0 0 0 0 0 0 3 3 3 3 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 3 3 3 3 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 3 3 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 4 0 0 0 0 0 5 5 5 5 5 5 0 0
0 0 0 0 0 0 0 0 0 0 0 0 5 5 5 5 5 0 6 0
0 0 0 0 0 0 0 0 0 0 0 0 5 0 5 5 5 5 0 0
0 0 0 0 7 0 0 0 0 0 0 0 0 0 5 5 5 5 5 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 5 5 5 5 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

Figure 4-36: Sample output of blob classification array

Additional code was added to return the (x,y) location of the blobs on the image. This comprised summing the x and y coordinates of all pixels inside the blob during classification then averaging the totals to give the centre point of the blob.

4.6.2.3 Algorithm output

After the algorithm finishes, it outputs the number of blobs found and their sizes and positions. It then compares the sizes of all classified blobs to find the largest.

4.6.2.4 Performance improvements

During testing, it was found that the recursive nature of the algorithm could cause java to crash due to a Stack overflow exception when dealing with very large blobs. This is because java has a limit on the number of times a function can call itself, as each function waiting to be run must be stored in memory. With the first implementation, a new level of recursion is created for each pixel classified within a blob, causing the potential recursion level to be limited only by the number of pixels in the image.

In order to fix this problem, the algorithm was modified to incorporate an iterative scan along the line of pixels at each level of recursion before calling the function again. This reduces the potential number of recursions by a huge amount, being limited by the height of the image rather than the total number of pixels, solving the stack overflow error. The modification also greatly improved the algorithm's speed and performance.

4.6.2.5 GUI development

A graphical user interface was designed and implemented for the robot client to enable user control and monitoring of the blob detection algorithm. This provided capability for:

- Starting and stopping the algorithm remotely.
- Adjusting temperature and blob size thresholds for calibration.
- Displaying the result of the binary thresholding.
- Monitoring the blob size and location calculated by the algorithm.

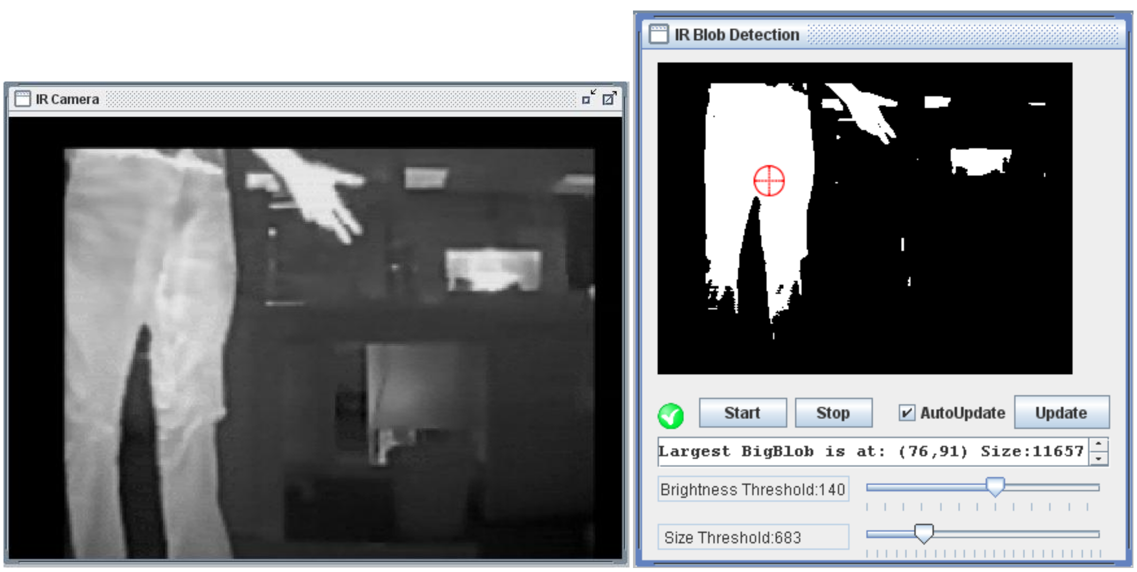


Figure 4-37: The GUI in action

4.7 Robot Arm

The sensor arm should provide a stable platform with larger torsional stiffness than the 2008 design whilst remaining lightweight.

Servomotors in the sensor arm shall be substantial enough to take the weight of the sensors without the need for counterweights.

Kinematic control shall be fully implemented.

The robot arm is the primary sensor platform and is mounted at the front of the robot. It shall carry the primary means of victim identification. The 2008 design lacked torsional stiffness in the lower section causing wobbling during movement. There was also no control of the arm and it was fixed in place.

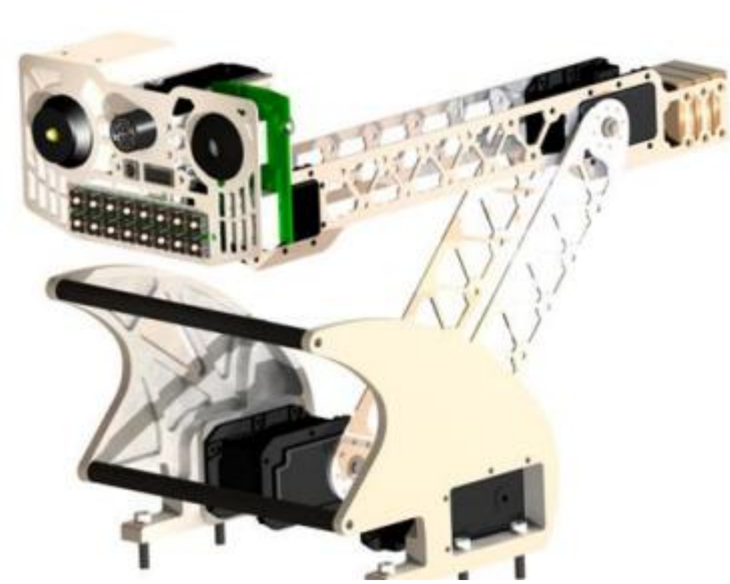


Figure 4-38: Robot arm at the 2008 competition

Due to the large camera mass at the end of the arm, a counterweight was needed at the elbow joint. This limited the amount of connecting braces that could be used between the two steel sheets making up the lower section. Figure 4-39 below shows that the lower section of the arm had only 3 connecting braces.

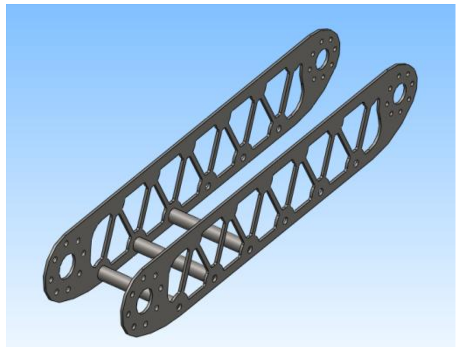


Figure 4-39: 2008 lower robot arm

4.7.1 Redesign

If the counterbalances could be removed then the stiffness of the lower section could easily be increased. The increase in height of the back robot compartment to house the extra flipper motor provided additional motivation (Figure 4-40) since the counterbalances clashed with the back section when docking the arm.

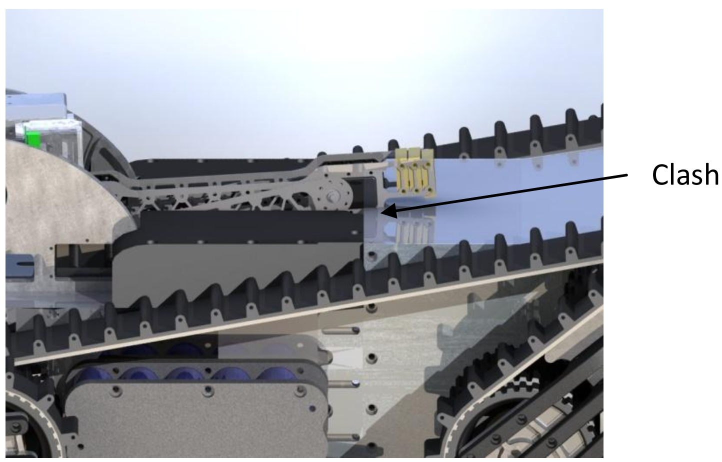


Figure 4-40: Clash between the rear section and counterbalance

Using a larger RX64 servo motor at the elbow joint, in place of and RX28, removes the need for the counterbalances. The RX64 can deliver over twice the torque.

RX64 maximum torque 6.28 N m

RX28 maximum torque 2.78 N m

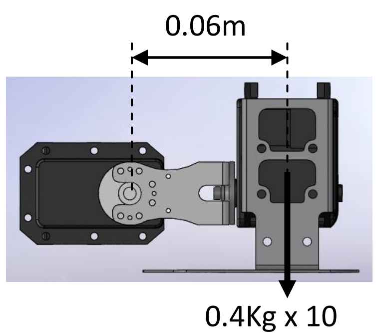
RX10 maximum torque 1.21 Nm

Table 4-8: Mass of arm components

Component	Mass (kg)
Sensor head	0.41
Upper Arm	0.133
Lower Arm	0.125
RX64	0.13
RX10	0.68

Torque diagrams show distances in metres and forces in Newtons.

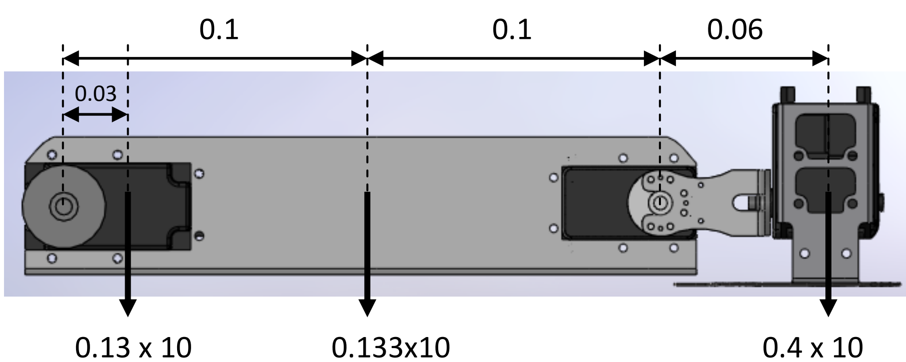
RX10:



Torque on RX10:

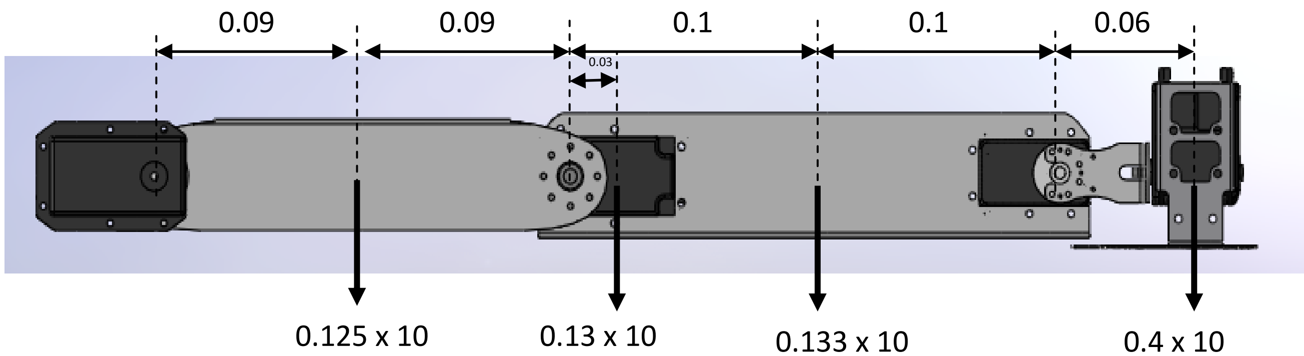
$$(0.4 \times 10)(0.06) = 0.24 \text{ Nm}$$

RX64



Torque on RX64 elbow joint:

$$(0.03)(0.13 \times 10) + (0.1)(0.133 \times 10) + (0.26)(0.4 \times 10) = 1.212 \text{ Nm}$$



Torque on bottom RX64:

$$(0.09)(0.125 \times 10) + (0.21)(0.13 \times 10) + (0.31)(0.133 \times 10) + (0.47)(0.4 \times 10) = 2.6778 \text{ Nm}$$

As can be seen from the calculations above, the maximum torque of the servomotors is not exceeded in this design. The servos are operating at least 2 times below their rating.

The RX64 is physically larger that the RX28 which requires that both arm sections are redesigned. Before the arm could be redesigned it was necessary to identify the weaknesses in the 2008 design so that requirements for the new arm could be made and targets could be set in order to achieve this.

4.7.1.1 Grabber

Using the larger, overrated RX64 servo on the elbow and two on the base allows the arm to carry a higher load and enable a new head design to incorporate a manipulator in the future.

4.7.1.2 Analysis of 2008 design failure

The main weakness of the 2008 robot arm was the failure to resist torsion (twisting), especially in the lower arm section. By modelling the arm as a simple beam and measuring the second moment of area along the z-axis of the arm the objects ability to resist torsion was found. However, the deflection of a beam under loads depends not only on the load but also on the geometry of the beams cross section. Hence the measuring of the second moments of area of each arm proved difficult since the arm sections have non-uniform cross sectional areas.

This led to the decision to analyse the weakest and strongest point of each arm, (where there was the least and most material respectively at a certain cross section along the object), and to use an engineering insight to analyse what targets are required to increase the torsional stiffness of the robot arm.

4.7.1.1.1 Analysis of lower robot arm

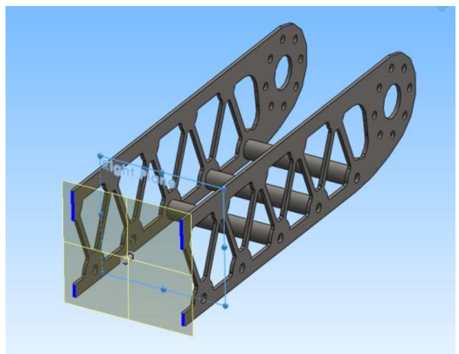


Figure 4-41: SolidWorks section-view feature

The arm models designed in SolidWorks were analysed with the aid of the section-view feature that allowed the largest and smallest cross-sectional areas to be found, as shown in the image on the left.

The lower robot arm has already been identified as being particularly weak in torsion along the z-axis from practical tests. Hence the second moment of area will be measured at the strongest and weakest parts of the arm and a brief structural analysis will conclude the targets for the redesign of the part.

<u>Weakest point</u>

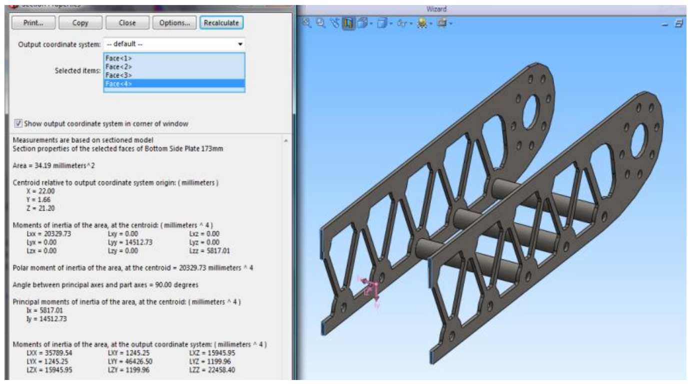


Figure 4-42: Section properties feature of SolidWorks

The section properties feature in SolidWorks analyses the selected cross section and identifies the centre of mass with a pink set of axes, from this the second moment of area is calculated in a matrix along all possible axes from the identified origin. The value that measures the second moment of area along the z-axis, down the middle of the arm is L_{zz}. The cross-sectional area of the section is also measured; the following analysis will largely feature these two values in the comparison, since the torsional stiffness depends on the amount of material in the cross section.

The weakest point of the lower robot arm only has an area of 34mm^2 according to the section properties feature; leading to a second moment of area along the z-axis of 5817mm^4.

Cross sectional area = 34mm^2

Second moment of area = 5817mm^4

<u>Strongest point</u>

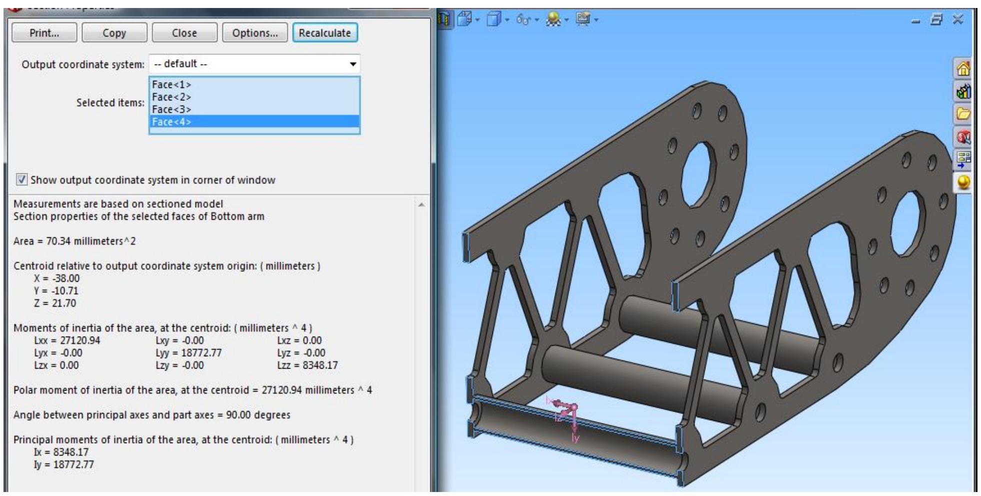


Figure 4-43: SolidWorks analysis of strongest point of lower arm

The cross section with the largest area is one that considers a section through the middle of one of the connecting braces, since this will allow the greatest cross sectional area; unfortunately the connecting braces are hollow so there is not a considerable increase in material in the cross-section.

The centre of the mass of the cross section acknowledges that there is a greater proportion of mass towards the bottom of the section and the pink axis origin is closer to the bottom of the section than in the previous analysis.

Cross sectional area = 70mm^2

Second moment of area = 8348mm^4

<u>Conclusion</u>

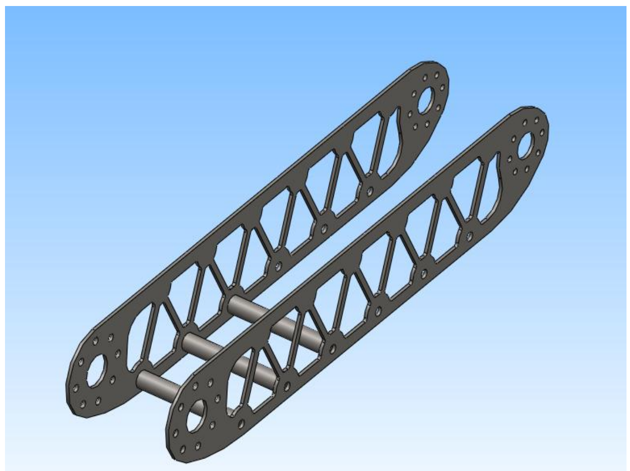


Figure 4-44: 2008 lower robot arm bracing

From the analysis it is obvious that the arm is strongest where the braces connect the two steel sheets, however, due to the counterbalances on the upper arm some clearance must be left at the end of the arm. This leads to a much weaker design and the most deflection is observed in this area in practical tests.

The main target for the redesign of this section of the arm is to increase the material in the cross section throughout the length of the arm with the aim to achieve a greater torsional stiffness that is clearly lacking throughout the body.

4.7.1.1.2 Analysis of upper robot arm

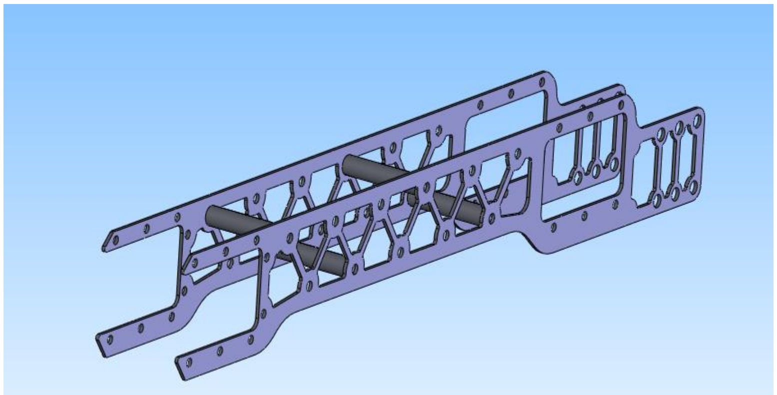


Figure 4-45: SolidWorks model of 2008 the upper arm

The image above shows the two steel frames of the upper arm with four connecting beams as used in the 2008 robot. By analysing the areas with the largest and smallest cross sectional areas, the frames resistance to twisting can be better understood as before with the lower arm.

Weakest point

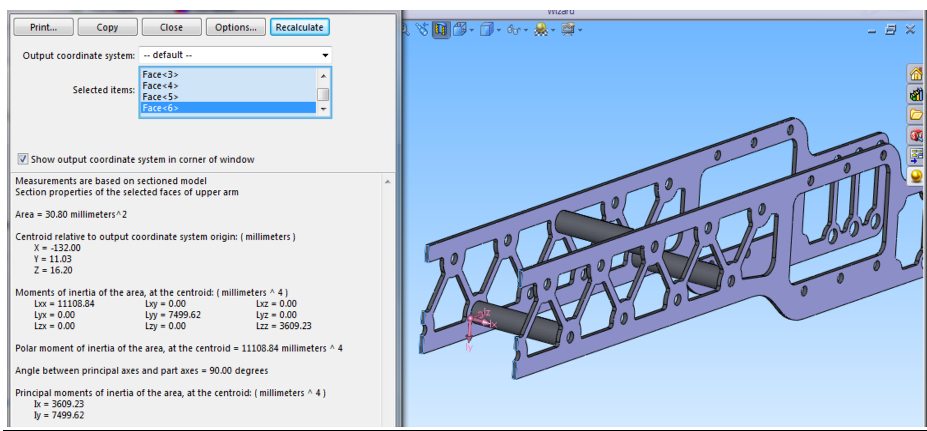


Figure 4-46: Section analysis by Solidworks

Using the cross-sectional analysis feature in SolidWorks, the smallest cross-sectional area was found to be 30.80mm^2 and the second moment of area along the z-axis was 3609.23mm^4.

Cross sectional area = 30mm^2

Second moment of area = 3609mm^4

Strongest point

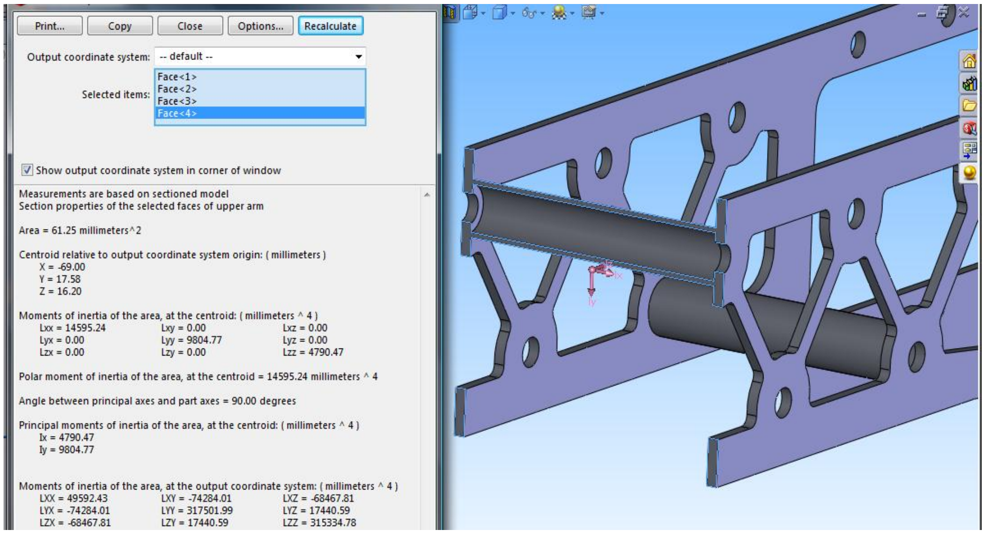


Figure 4-47: Section analysis by Solidworks

The strongest point of the frame was a cross section through the middle of one of the connecting braces, giving an area of 61mm^2 and a second moment of area of 4790mm^4.

Cross sectional area = 61mm^2

Second moment of area = 4790mm^4

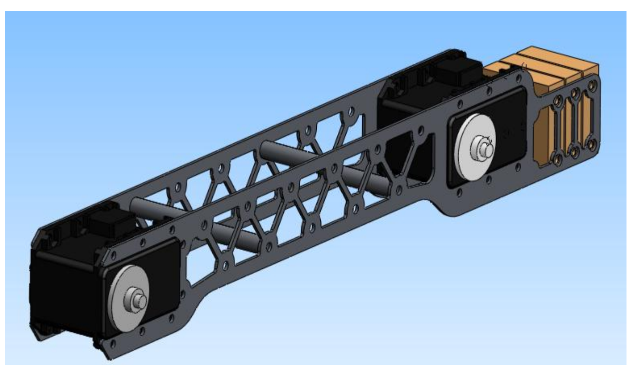


Figure 4-48: Full upper robot arm

Conclusion

Both the strongest and weakest second moments of area of the upper arm are lower than the corresponding strongest and weakest points of the lower arm; however the upper arm is more structurally rigid due to the more effective distribution of connecting braces on the top and bottom of the beam. The upper robot arm also has additional resistance to torsion at both ends due to the RX-10 and RX-28 servomotors being attached to the frame. Along with the 4 connecting braces between these two servomotors, the upper robot arm is much more resistant to torsion than the lower robot arm.

4.7.1.2 Redesign Options

1. The offset arm

The analysis of the second moment of area suggests that using aUsing square cross-section steel piping the arm would have greater resistance to deflection but the sections must be offset for the greatest range of motion and so they can collapse.

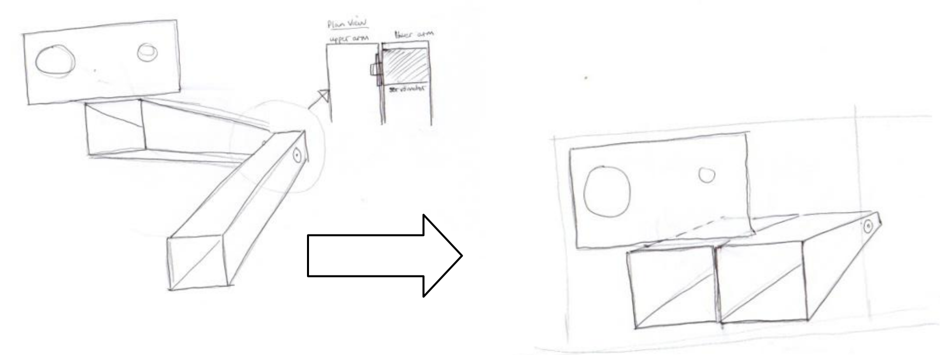


Figure 4-49: 2009 arm concept design 1 - square box section offset arm

2. The U-section arm

With a U-section the arm can still fold into itself in a similar manner to the 2008 design.

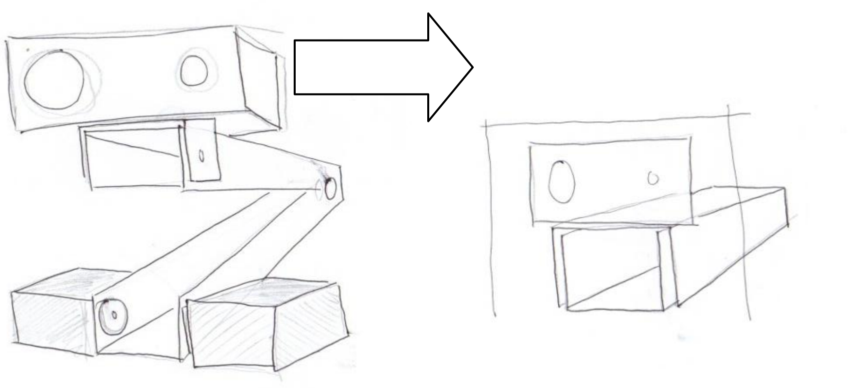
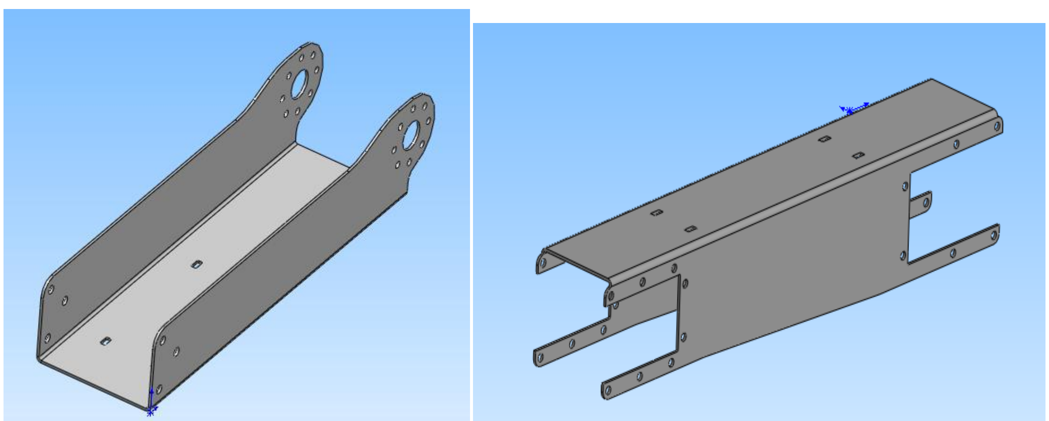


Figure 4-50: 2009 arm concept design 2 - U-section arms

The U-section was considered the best option since although the square box section would provide greater torsional stiffness, it would also place greater strain on the motor at the elbow joint and would be difficult to access for maintenance since it would be fully enclosed.

4.7.1.3 CAD Modelling



4-51: designs of new arm sections

4.7.1.2.1 Torsional Stiffness

The SolidWorks modelling system provides quick analysis of new designs and the above images show the final parts that were produced. The section properties tool was used to calculate the torsional stiffness of the new design.

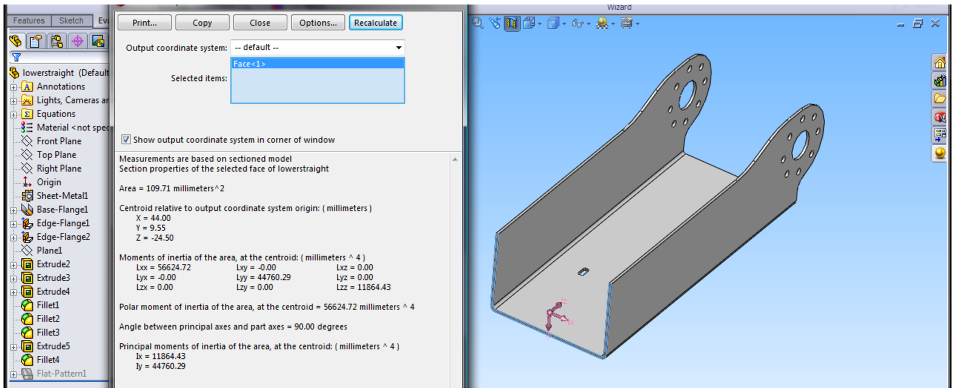


Figure 4-52: Section properties of lower arm design

Cross sectional area = 110 mm^2

Second moment of area = 44760 mm^4

From this calculation it can be seen that the cross sectional area is now even greater than the strongest section of the previous year's design and this provides an improved torsional stiffness since the second moment of area along the z-axis of the part. The same applies to the new upper arm since it has a similar improved uniform cross section.

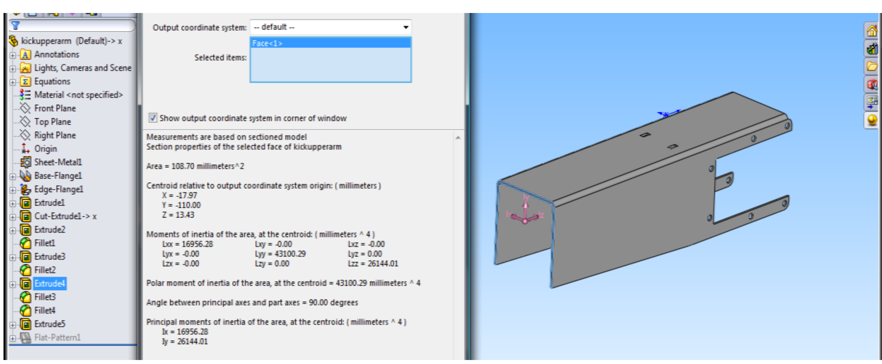


Figure 4-53: Section properties of upper arm design

Cross sectional area = 108 mm^2

Second moment of area = 26144 mm^4

4.7.1.3 Manufacturing

The arm sections are to be manufactured from sheet metal (316L 0.9 mm stainless steel). Figure 4-54 shows the flattened sheet metal drawing that will be laser cut and folded at 90° along the edges, with bottom extension riveted for ease.

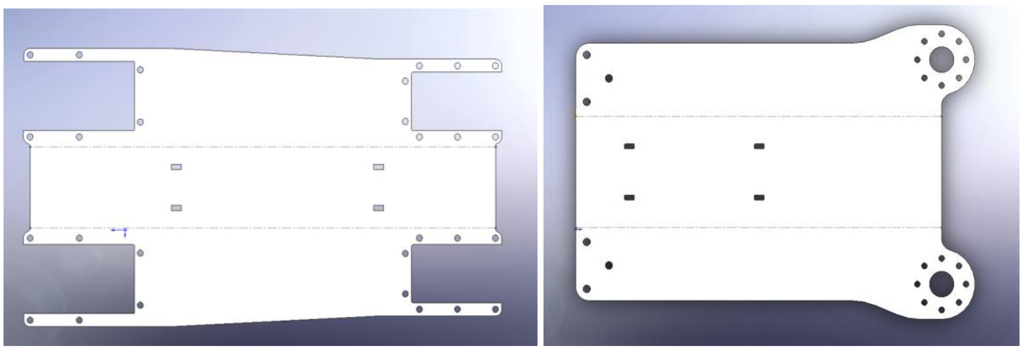


Figure 4-54: Flattened sheet metal for arm sections

4.7.1.4 Roll Cage

The rollcage has been widened for safer docking of the sensor head. Extensions have been designed so the base servos can still fix to the roll cage.

Figure 4-55: Arm in roll cage with servo mounting extensions visible

4.7.1.5 New Face Plate

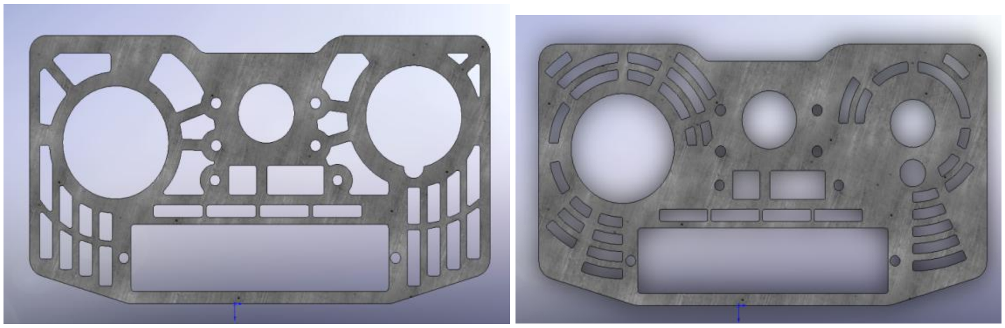


Figure 4-56: Old and New Face plates

A new faceplate was also manufactured, with a new location for the CO_2 sensor.

4.7.2 Kinematics

The forward kinematics were calculated and using the Denavit-Hartenberg Conventions, the full calculations can be found in the Appendix A.

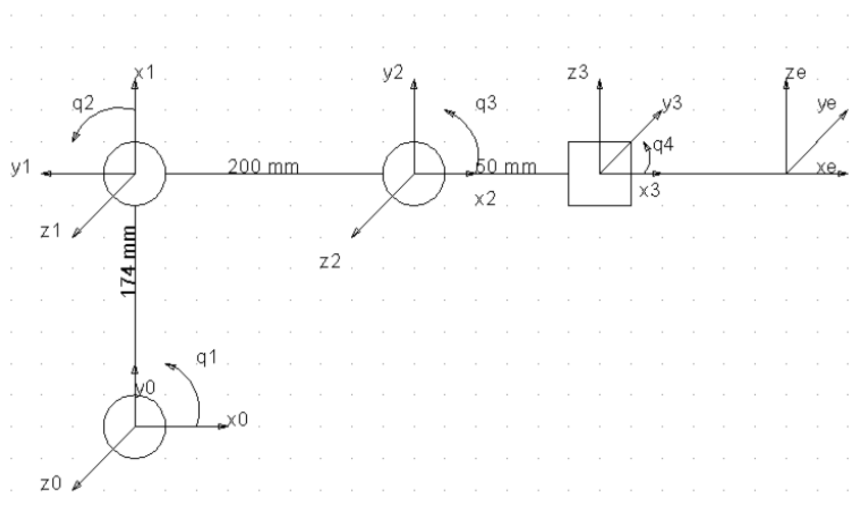


Figure 4-57: Arm in home position

Table 4-9: DH Parameters

Link i	a_i	α_i	d_i	θ_2
1	174	0	0	90°+q_1
2	200	0	0	q_2-90°
3	0	-90°	0	q_3
4	0	0	0	q_4

Evaluating the transformation matrices leads to the result that angle q_3, the head tile angle, depends on the angles of the two arm joints. To set the head looking at an angle relative to the horizontal the following equation is used:

$$q_3 = \angle x_e - q_1 - q_2 \qquad (1)$$

Setting $\angle x_e$ to the desired look angle above the horizontal with known q_1 and q_2 angles gives the required angle for q_3.

The forward kinematics are suitable for determining the effects of independent joint control however it is desirable to move the arm in Cartesian coordinates to allow easy input of preset positions (for example driving, overhang look, forward victim examination). The inverse kinematics summarise as follows:

$$d = \sqrt{x^2 + y^2} \qquad (2)$$

$$\phi = \tan^{-1} \tfrac{y}{x} \qquad (3)$$

$$q_2 = \cos^{-1}\left(\left(\frac{a_1^2 + a_2^2}{2a_1a_2} - \frac{d^2}{2a_1a_2}\right)\right) \qquad (4)$$

$$q_1 = \tan^{-1}\left(\frac{a_2 \cos q_2 + a_1}{a_2 \sin q_2}\right) + \phi \qquad (5)$$

Substituting the link lengths leads to an expression for q_2 and q_1 that can be implemented in software.

$$q_2 = \cos^{-1} \; -\tfrac{17569}{17400} + \tfrac{169600}{} d^2 \qquad 6$$

$$q_1 = \tan^{-1}\left(\frac{200\cos q_2 + 174}{200\sin q_2}\right) + \phi \qquad 7$$

The q_3 angle is set as in Equation 1.

4.7.2.1 Planar Kinematic Control

Using the inverse kinematics the arm can be moved in xy-coordinates relative to the arm base. The head look angle, with respect to the horizontal, remains constant for any combination of base and elbow angles until user modified. Pressing a “move arm” button on the controller moves the arm a fixed distance in the x or y direction. The robot moves through a number of points on route where the q_3 angle is evaluated to maintain the look angle and giving much smoother movement.

Presets, such as a driving position and docked, are stored in computer and the arm moves through a safe path to reach these points.

The docked position is with the head inside the roll cage which protects the expensive and fragile cameras should the robot topple. The roll cage is a tight fit so a number of preset positions are moved to in order to dock safely and the head first moves to looking forwards. An emergency dock procedure is under development which uses the full speed capability of the arm to dock in very short time if the robot is toppling.

The driving position is at the back of the robot with the front flippers in view. This gives a view of as much of the area in front of the robot as possible and also matches the driving position of the Northrop Grumman Cutlass bomb disposal robot.

Dynamixel servos are used for each joint. These are addressable over a bus (RS485) and communication with the computer is performed using a USB converter. The desired angle is sent (with appropriate offset for the servo’s home position). Limits are applied in software to the angles to prevent the arm attempting to reach impossible configurations in terms of maximum and minimum angles and also positions outside of its workspace in kinematic control. These servos also feature overload protection and shutdown if they are attempting to provide too great torque which would damage them.

4.8 Mapping

The mapping technique used on the robot is based on a simple Simultaneous Localisation and Mapping (SLAM) algorithm.

The algorithm is based on image correlation where it attempts to locate and rotate the current LiDAR scan to best fit the map. The scan is then overlain on the map at the calculated co-ordinates.

As image correlation is very computationally intensive, steps have been taken to optimise the algorithm. These steps include reduction of the search area to within what the robot could physically move within a few seconds and within ninety degrees of its previous heading.

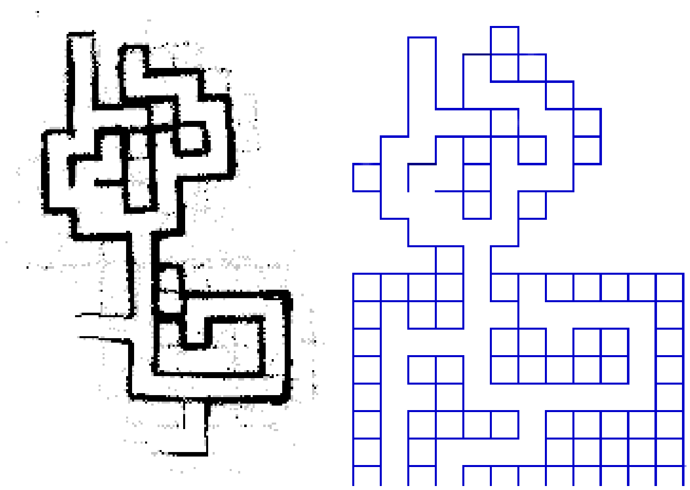


Figure 4-58 Comparison between Map and Arena produced by the simulator

The image correlation algorithm is based on a simple scoring system where the more pixels of the LiDAR scan that overlay the current map, the higher the score and thus the more likely that this is the correct orientation. The correlation with the highest score is declared the most likely position and added to the map.

4.9 Communication

The main communication is between the operator at a base station computer (client) and the robot computer (server). Using Wifi for connection between computers is an off the shelf solution and simple to implement. The IEEE 802.11a network specification is required by the competition for any wireless communication. Wired communication is impractical for a mobile robot in unknown terrain.

4.9.1 Low Lag Connection

4.10.1.1 Connection Type

The connection between the client and server is a TCP (Transfer Control Protocol) data socket. Although TCP is slower than a UDP (User Datagram Protocol) connection, the benefits of using TCP outweigh the disadvantages. One of the main benefits is guaranteed delivery; if the wireless connection is interrupted for a second or two the message will not be lost. UDP is a form of streaming with no handshaking or error checking, so delivery of messages is not guaranteed. This introduces possible dropped communication so for better reliability TCP was chosen.

4.10.1.2 Authentication

As motor and power control commands are sent through this connection it is vital that there is some level of authentication in order to gain access to these systems. Otherwise a third party could easily interfere with the robot.

When the connection is initially opened by the client the server sends a welcome message and a request for a password. The password of which is sent to the client using the standard object connection at login. The password serves two purposes, not only does it verify that the user should have access to the robot but it also binds the socket to the client on the server.

The password is a universally unique identifier (UUID) generated on each new connection to reduce the risk of duplicate passwords.

Figure 4-59: Automatic Initialisation and Authentication of the RLLC

4.10.1.3 Data Protocol

For simplicity and ease of use all the commands are human recognisable. Although this means that the data transfer is not fully optimised it does allow for the user of the client to understand and manually send commands.

A full list of currently supported commands can be viewed in Appendix B.

4.10.1.4 Client Side

Apart from complying with the authentication procedure, the client does not format or process the incoming or outgoing data in any way but merely acts as a bridge between the server and the class sending a request. This reduces the overheads and complexity of the communication.

4.10.1.5 Server Side

The server sorts and executes all of the commands that are sent by the clients. When a client sends a request/command, the server first checks to see whether the client is authenticated and then searches its database of commands and executes the associated functions on the robot.

4.11 Navigation

Several sensors are used for the navigation in both autonomous and tele-operated modes. In addition to those described below, an electronic compass and IMU was investigated. This testing is described in Section 5.1 Component Testing.

4.11.1 Tele-Operation

The graphic user interface on the client must provide all information used by the operator to control the robot.

4.11.1.1 Robot State Diagram

To aid the operator in visualising in what position the flippers and arm are in, a diagram depicting the robot in its current state was created.

As the rear flipper motor uses a relative encoder the position of the rear flipper needs to be synchronised with the diagram in order for it to be correctly displayed.

The joint angles of the arm are calculated using the same inverse kinematics algorithm as the robot to create an accurate representation of the position of the arm.

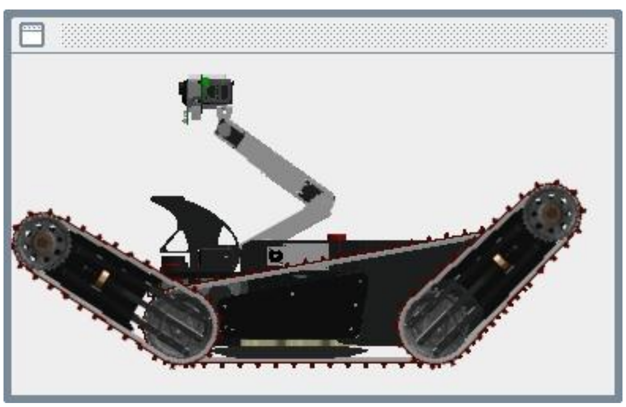


Figure 4-60: Robot state GUI

The diagram itself is comprised of multiple images that have been exported from a SolidWorks render of the robot. Each image is then rotated and placed into the correct position to draw the diagram seen in Figure 4-60.

4.11.1.2 Toolbar

The toolbar was added so that the operator of the robot can quickly and easily access certain commonly used functions as well as several safety functions such as remote E-stop. The most frequently used buttons have contrasting colour schemes to reduce the chance of the operator pressing the incorrect buttons when driving under stress. The buttons indicate the current status of the features.

Figure 4-61 Screenshot of the toolbar

4.11.1.3 Arm Presets

As it can be slow and disorienting for the operator to manually move the arm large distances whilst driving, an arm preset manager was developed. This enables the operator to at the click of a button to move the arm into multiple preset positions. The manager takes the form of a simple GUI with several presets for the arm and is easily expandable for future developments.

The currently implemented presets include a driving position where the head is as far back from the front of the robot as possible to get the widest field of view, a neutral position "start-up" which is central to the robot and a position which looks down over the front of the robot.

Figure 4-62 Arm preset manager

These presets also ensure that the arm does not move to an unsafe position where it could damage the servos. Manual control is possible using buttons on the game controller.

4.11.1.4 Vital Robot Statistics

This window displays the current CPU temperature of the robot computer and the robot’s battery voltage. Battery voltage monitoring is very important as it gives an indication how much longer the robot can be run on the current set of batteries. The battery voltage is read from the AX3500 motor control board.

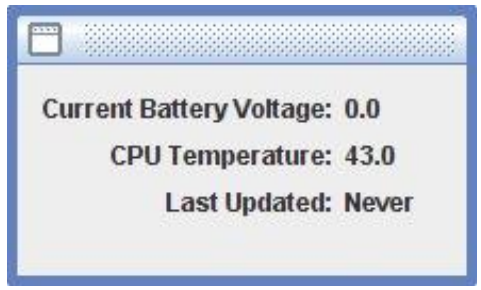


Figure 4-63 Robot Stats Reporter

4.11.1.5 Game Controller

The primary means of driving the robot is using a game controller attached to the client computer. An improvement to the 2008 implementation know checks for rising and falling edges on the controller buttons to ensure that only one move command is sent for each button press (except the analogue sticks for the drive motors where a change in stick position sends a command). The controller is scanned approximately every 20 ms which is ten times faster than 2008 aiming to reduce lag on the controls.

4.11.1.6 Webcams

The forward facing Axis 207 and rear facing Axis 206 Ethernet cameras are displayed in the GUI when connected to the robot. The forward camera is mounted on the robot arm so can be manoeuvred to give the best driving view.

4.11.2 Autonomous Operation

4.11.2.1 PieEye

For the first version, the PieEye model was divided into seven slices. This meant that each slice covered 34.29°. ($\frac{240}{7} = 34.29°$)

The key functions contained in the PieEye class are

1. **'Bake' pie** - gather data from LiDAR scan and allocate into slices calculating each slice's 'tastiness' value (an average of all distances within the slice).
2. **Is path clear?** - checks the tastiness value of each slice against a preset threshold in order to detect possible collisions or blocked paths. Biases can be applied to the tastiness values in order to alter the area of sensitivity, for example higher sensitivity to collisions in forward-facing slices and less to those on the side.
3. **Get best path** - analyses the PieEye data in order to gauge the best path to take. This normally means picking the slice with the highest tastiness threshold (the most open) but biases can also be applied to influence the decision. The angle of this slice is then passes to the turn function.

4.11.2.2 Improvements after testing

4.11.2.2.1 Increasing number of slices

One major problem identified during testing in the simulator was the lack of resolution offered by a seven slice system. This meant that there could be a large degree of variation within a slice (for example a slice containing a thin, close obstacle surrounded by open space would be seen as more preferential than a slice full of middle-distance obstacles once averaged). It also meant that the robot found it difficult to detect thin obstacles. This problem was fairly easily solved by increasing the slice number to 31, made possible by the flexible nature of the PieEye framework. This reduced the slice size to just less than 8°, making small obstacles easily identifiable and increasing the accuracy of the best path finder.

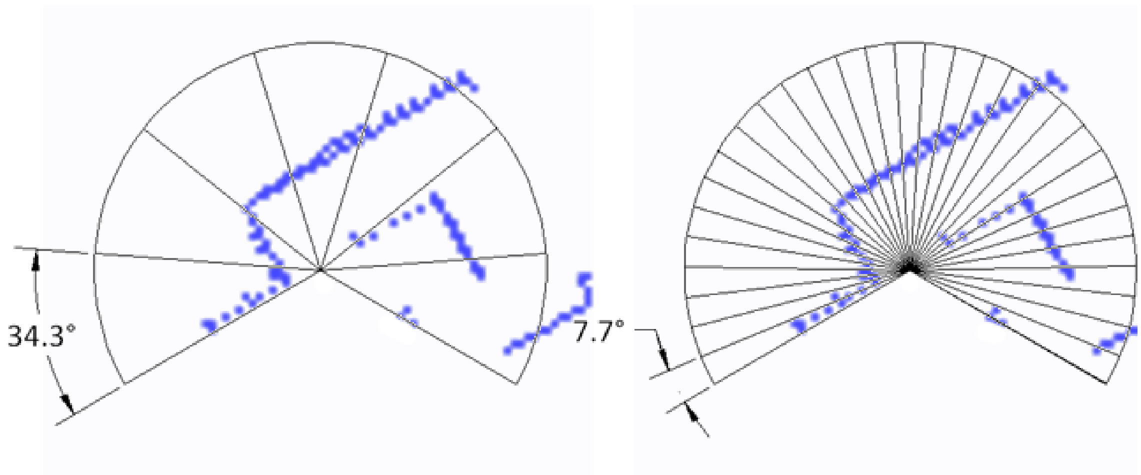


Figure 4-64: Increase in number of PieEye segments

4.11.2.2.2 Collision Severities & Dynamic Biasing

Another problem identified was the selection of headings very close to obstacles. This is due the discrete nature of the PieEye slices, whereby the presence of an obstacle in one slice would not prevent the AI from choosing a close neighbour as a heading. A two-stage solution was created to solve this issue.

Firstly, during the ispathclear? function, any slices identified with potential collisions were assigned a severity level (from 1 to 5) based upon the proximity of the obstacle detected. From these collision severity levels, dynamic biases were then applied to the getbestpath function. This involved not only biasing against slices where a collision was detected but also its surrounding neighbours. The width and strength of this biasing was defined by the severity level of the collision.

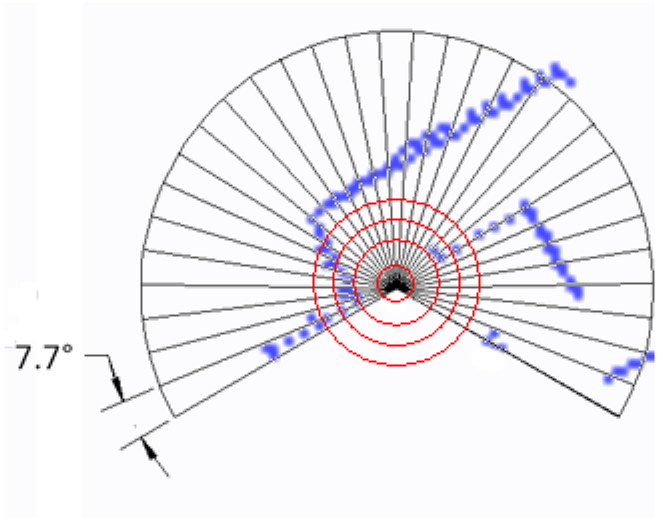


Figure 4-65: Addition of severity levels

4.11.2.2.3 Intelligent Turning

Initially the robot used a system of dead-reckoning when turning under AI control. This involved calculating the time taken to complete a full revolution then scaling this time to achieve the desired turn angle when required. However this odometric approach proved inaccurate as the robot is tracked and therefore slips a great deal during its turn. Differing friction coefficients of different floor surfaces also meant that this method was very inconsistent for varying environments.

A new approach was devised, utilising LiDAR data to measure the angle by which the robot had turned.

1. An initial snapshot was taken of the LiDAR scan and stored in memory.
2. Turning is initiated and every 100 ms, a new LiDAR scan is taken and cross-correlated against the initial scan. This cross-correlation function outputs the offset (in LiDAR points) between the initial and current scans. From this, the angle turned can be easily calculated.
3. Every 30° the function takes a new snapshot, overwriting the initial one, in order to make sure the cross-correlation function always has a relatively full LiDAR scan to work with.

After testing various AI navigation strategies using the simulator and test rigs (Section 5.1) it was observed that most collisions occurred as the robot turned. So it was decided to implement collision detection as a part of the intelligent turning function.

This operates using the same PieEye ispathclear? function but applying heavy biasing to only focus on areas within the robot turning circle and in the direction of turning. If an imminent collision is detected, the turn is aborted and a new best path is calculated.

4.12 Manipulation

The robot arm is designed to lift more than the weight of the cameras mounted on the head. This should allow future development of a manipulator.

4.13 Simulator

The simulator allows development of robot software while the robot itself is unavailable through failure or current upgrading.

4.13.1 Initialisation

4.13.1.1 Modelling the Arena

The virtual arena is modelled and inputted into the simulator using a bitmap image. Each pixel represents an area of 10 cm by 10 cm, currently only the blue primary colour is used by the simulator with red and green being available for future development.

In the current version of the simulator the value of the blue component denotes height, allowing the user to create three dimensional arenas (0x00 and 0xFF is zero height and the numbers between 0x01 and 0xFE represent increments of 1 cm). Figure 4-66 shows a two dimensional arena of which has been used extensively for testing the robot's autonomy and mapping.

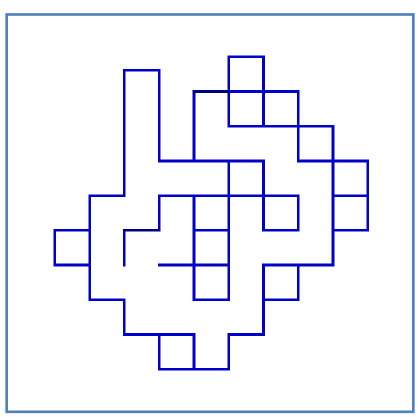


Figure 4-66: Example of a two dimensional arena

4.13.1.2 Loading Constants

Constants such as the robot's starting position, simulation time and the path to virtual arena bitmap is inputted at runtime before the simulation is started. This makes the simulator easier and faster to use as a single distribution of the simulator can run any scenario.

4.13.2 Emulated Server Components

In order to make the autonomy and mapping algorithms fully compatible with the actual robot, the vital components and interfaces of the robot have to be emulated. This ultimately allows the code, after it has been tested, to be simply copied and pasted straight into the robot's source code, reducing errors when updating the robot software to match the simulated functions.

The emulated server components include (these components are documented in the 2008 WMR Technical Software Report(13)):

- Control Marshall – For motor commands
- DataStore – For sensory data

4.13.3 Emulated Sensors

Currently only the LiDAR scanner is simulated. However, the simulator is designed to be modular so that adding extra sensors such as encoder and sonar data does not require a major change.

4.13.3.1 LiDAR

The LiDAR sensor is emulated by using the virtual arena and the robot's position and orientation.

To generate a LiDAR scan the algorithm firstly takes a snapshot of the robot's surroundings from the map (see Figure 4-67(a)) the map is then rotated and the three dimensional offsets are calculated based on the robots height, pitch and roll. Figure 4-67(b) shows the output of this algorithm, as this example is a two dimensional arena the extracted map will not be modified. The last step is to convert the Cartesian data into polar data of which only the closest values are saved. By applying this filter any walls that are not in direct view are filtered away, thus recreating a lifelike LiDAR scan. During the Cartesian polar conversion any points that are outside the LiDAR's set range are ignored and to simulate granularity the polar array has the same amount of points as the LiDAR being simulated (Figure 4-67(c)).

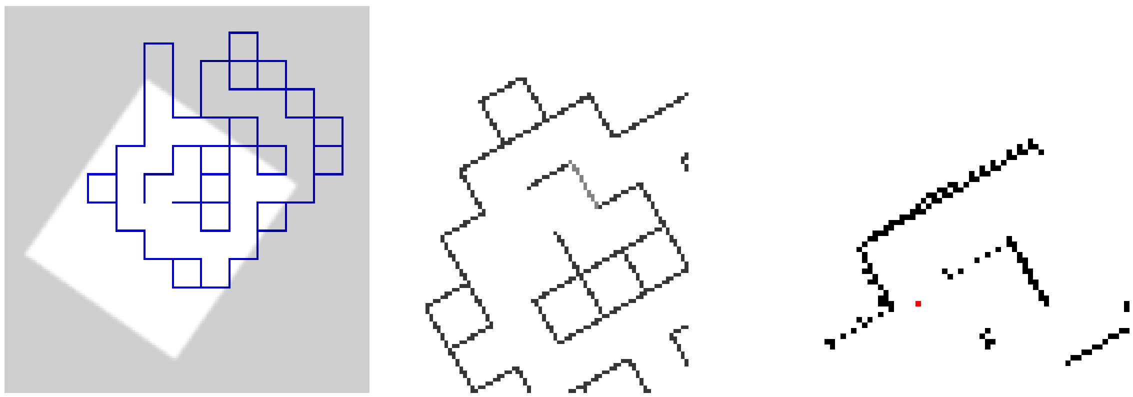


Figure 4-67: Left to right (a) LiDAR scan area (b) Extracted and rotated map data (c) Filtered map data reconstructs LiDAR points

4.13.4 Output Visualisation

To save processing power when the simulator is running the logs are not output until after the simulation end timer has elapsed.

To make the simulation data easier to visualise the simulator overlays the robot's path and position onto the bitmap that was originally loaded and used for the virtual environment. As well as the path the simulator overlays extra data such as the current LiDAR view, robot's position in simulation units, the simulation time at which the record was logged and any additional debug data from the autonomy/mapping algorithms.

An example image of a log is shown in Figure 4-68. The red line is the breadcrumb of the robots path, the diagram inside the green box is the current simulated LiDAR scan and the text shows various useful simulator logs.

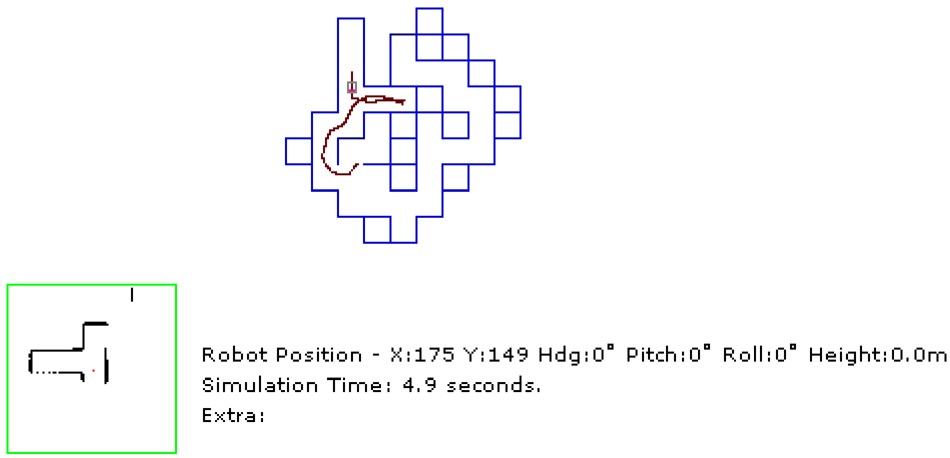


Figure 4-68: Example of simulator output

4.13.5 Error Handling

The simulator incorporates a watchdog that checks if any vital component of the simulator crashes while it is running. When an error is detected the simulation will end and the recorded logs up to the point of the error are generated.

4.14 Demonstration and Testing Arena

For demonstration and testing purposes terrain representing the competition arena is required. For full design see Appendix C for competition specification and Appendix A for production drawings.

Figure 4-69: WMR testing and demonstration arena

5 Verification & Validation

Systems are verified and validated by first testing system components and then integrating with subsystems and finally when integrated with the entire robot.

5.1 Component testing

Much component testing was performed during the design stage to inform design decisions. Testing of some aspects was performed after they were assembled before integrating with the rest of their subsystem.

5.1.1 Power Distribution Board

After population of the circuit board and programming of the microcontrollers, testing was performed using Hyperterminal to send the switching commands to the board. Initially the outputs did not switch and it was discovered that the N-channel MOSFET footprint was different from what was expected (D-G-S rather than D-S-G). The FETs were removed and replaced with ones with twisted over legs. The switching now works on all primary channels but additional FETs must be purchased to replace those on the auxiliary output channels (back row of connectors). Alternatively, shorting the drain and source pads will turn the outputs on permanently.

The heartbeat function and E-stop also operated correctly but the heartbeat was set to be off by default so that any bugs in the software on the power board or robot computer did not result in the robot always E-stopping. The heartbeat can be activated by sending an activation request and with further testing this should be changed to default on for safety.

The 18 V power supply also works giving 17.6 V which is suitable for powering the RX64 servos on the robot arm.

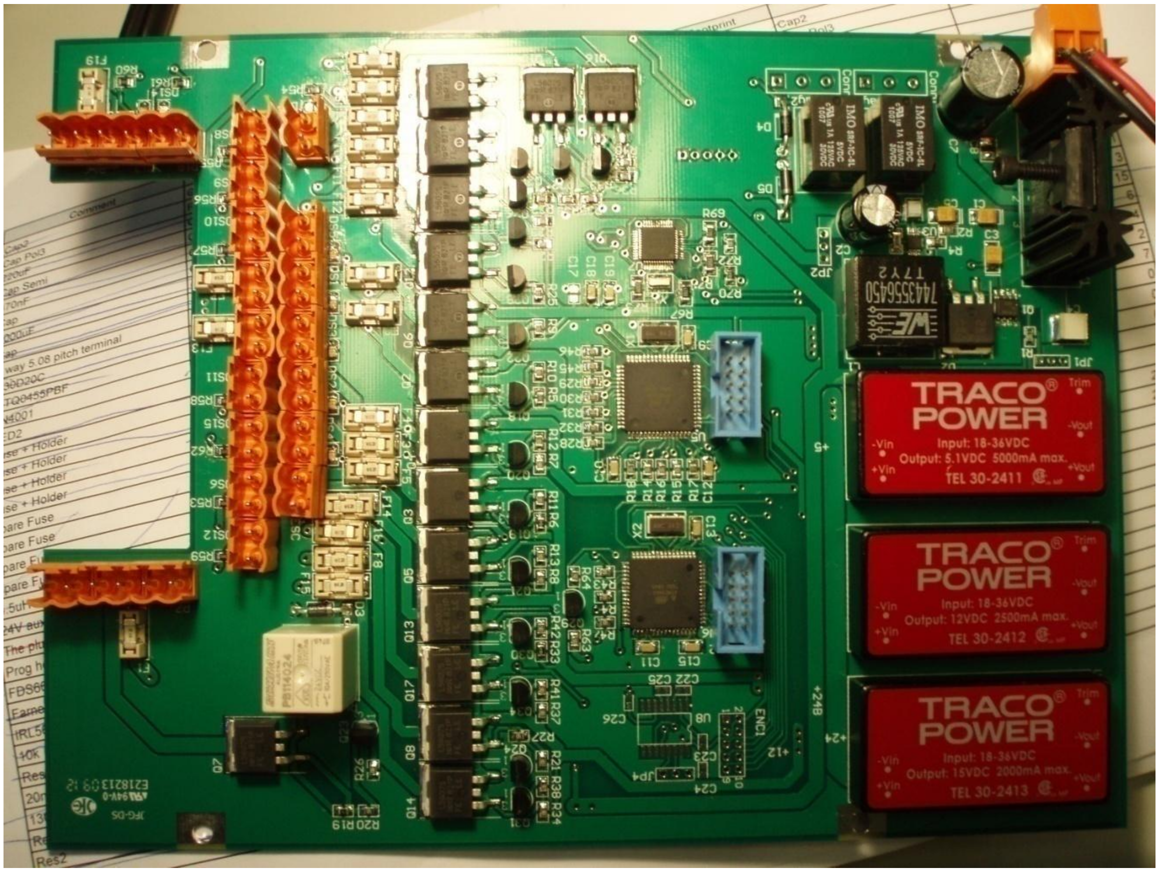


Figure 5-1: Populated power distribution board

5.1.2 PieEye Testing

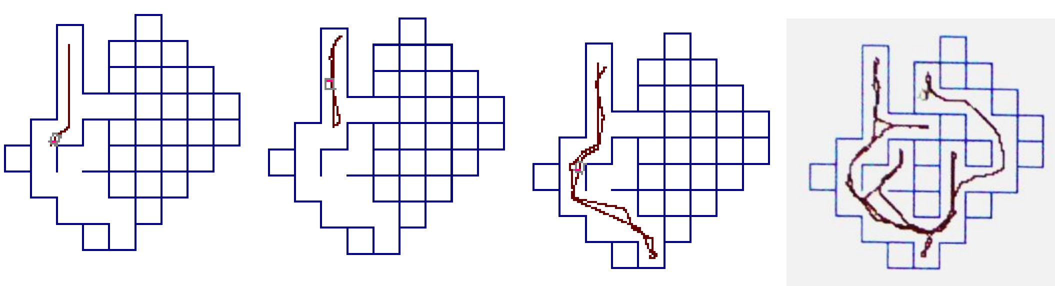


Figure 5-2: Simulator outputs showing strategy improvement

The primary test method for the autonomous navigation strategies was the simulator. This was very important during the early design stages as tests could be carried out without access to the functional robot (either due to working away from the laboratory or disassembly). The various parameters and variables could be tuned using a course similar to that expected in the competition arena.

5.1.3 Flipper Drive System Testing

The front and rear flipper drive systems where designed to utilise the same design of flipper split shafts (refer to Section 4.3.1.7)

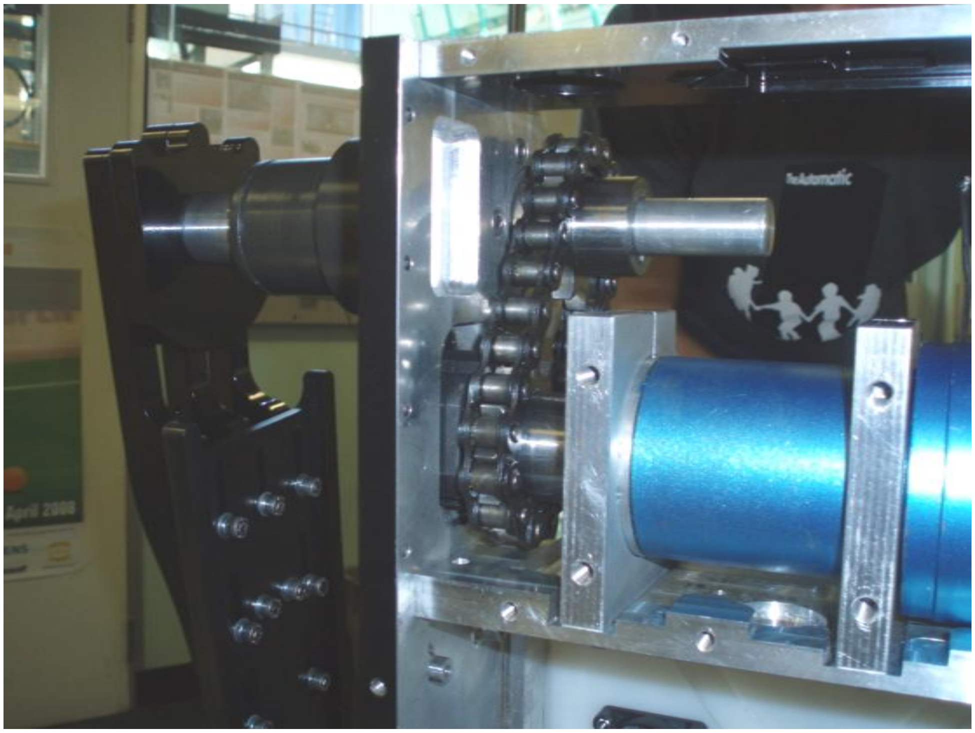


Figure 5-3: Front chain drive assembly

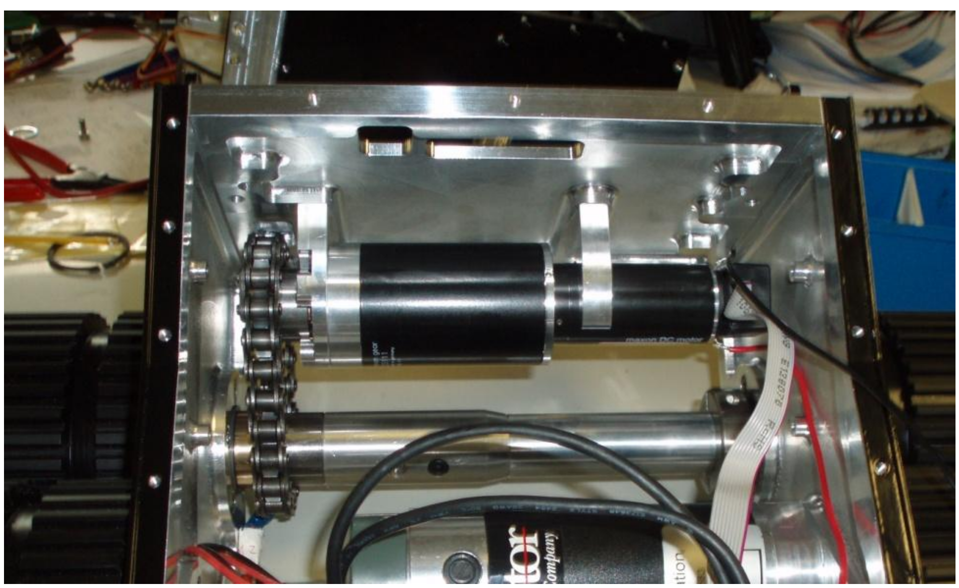


Figure 5-4: Rear chain drive assembly

Individual assemblies were tested using a 24v power supply to drive the motors directly and proved successful. It was not possible to test the assemblies running on full power and lifting the weight of the robot before the competition due to the delays in final assembly.

As expected the rear flipper arms could only move in steps of 15° (Section 4.3.1.5). This meant that the encoder counter had to be reset after every movement so the maximum rotation command could be re-sent to the AX3500 board. Due to some subtleties of the control boards the PID control did not operate in this situation and the motors rapidly accelerated and moved to the new maximum displacement. Such high accelerations are undesirable and could damage the gearbox though shock loading and high torque.

This meant that a maximum step of 15° could be achieved using position control before the control board counter needs to be reset for the rear flippers. This is similar to the distance travelled on the front flippers and was seen as acceptable. The Parvalux motor with its Hall Effect encoder does not have this problem as it is an absolute measurement of position. However, with the encoder set up as it is there is a dead zone where the encoder provides no output signal (Figure 4-14) where the flipper cannot pass through – preventing 360° rotation on the front flippers.

5.1.4 IMU and Compass

The Inertial Measurement Unit and electronic compass was tested in laboratory conditions and could provide useful information regarding robot orientation. The compass also provides tilt and pitch information and IMU gives angular velocities.

5.2 **Subsystem testing**

5.1.5 Navigation

5.1.5.1 Autonomous Operation

Figure 5-5: Autonmous navigation testing using Remotec test chassis

Once the strategy development was reasonably mature, testing was performed using the existing robot's power, sensor and control systems mounted on the test chassis donated by Remotec. This proved useful for demonstrating the challenges and differences between simulation and real-life operation. It what during this test phase that the problems with dead-reckoning turning and PieEye slice resolution were recognised.

5.1.6 Victim Identification

5.1.6.1 Tele-Operated Victim Identification

Once the tele-operating system had been created it was tested during competition for ease of use and assistance offered to the operator. Further development of the GUI layout could lead to faster start up times as currently windows have to be arranged each start up.

The blob detection GUI allowed at a glance the operator to determine if any heat sources where close by with the greyscale output could be used for a more detailed view when a blob was observed. Live thresholding allowed the operator to adjust setting on the go and to compensate for surrounding heat sources and limit the blob detections sensitivity.

A microphone system was set up but the delay experienced from the cameras over the network made it unsuitable for competition use where the run time was extremely limited. Webcams offered the greatest level of ID allowing for form, state and movement to be determined by the operator. Tags could also be identified and the "Tumbling E" test was possible down to the smallest letters.

The main difficulty identified was that of positioning the robot close enough for the head to be able to see in the tombs. It was found most successful to drive head on towards the victim allowing the full forward movement of the arm to be utilised for victim ID.

5.1.6.2 Autonomous Victim Identification

The heat detection algorithm was developed as a separate Java project within the development environment to enable it to be tested and run separately to the robot, whilst using the same sensor interfaces.

5.1.7 Robot Arm

While the robot was non-operational, the robot arm and roll cage was mounted to externally whilst the kinematic control of the arm was tested. The wrist can be moved vertically and horizontally while maintaining a constant look angle. Pan-tilt operation of the wrist was also successful.

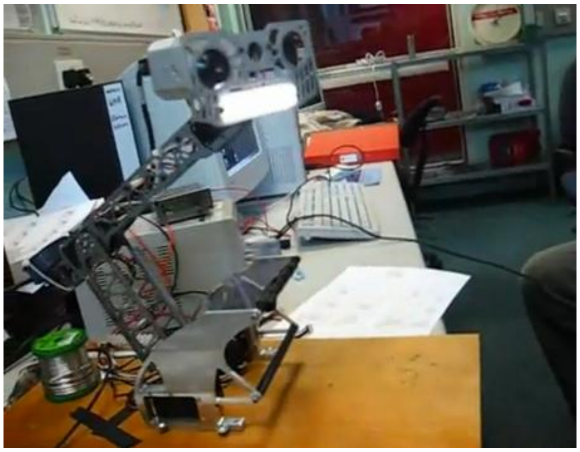


Figure 5-6: Test bench for arm

5.1.8 Power Systems

5.1.8.1 Motor Power

After performing well in power applications such as the ramp climb early in the week the robot seemed to lack the power required to climb obstacles during later runs. On the final days of the week power so lacking the robot struggled to make small gradient climbs. To remedy this the batteries where changed for a fully charged pair but this made no difference. It was concluded that the main safety relay was responsible as it was only rated for 70 amps, whereas the motors could draw notably more than this as a pair. This did not explain the previous success at these obstacles.

5.1.8.2 Wiring

When connecting the power from the inputs (batteries and mains) between the three sections of the robot (front, rear and centre) it was identified that using power poles between sections was impractical due to their size but it was essential to retain the modularity by using connectors. A screw terminal chocolate-block is used in the rear section for the motor power supply (to the AX3500 boards) and a 10 A orange connector for the front flipper motor.

5.1.8.3 Run time

The robot ran for 30 minutes over competition terrain before the batteries were too weak for further use on difficult obstacles. Casual use on flat, low-friction surfaces was possible for over 2 hours and on a bench with no motors the robot ran for over 6 hours. This meets the specification on operating time.

5.1.8.4 Emergency Stop

The emergency stop relay is rated to 70 A. With two LiPo batteries the drive motors were able to draw more current when attempting stairs and steep ramps. This heated the relay and caused it to fuse closed preventing the emergency stop functions from operating. When the relay cooled down the E-stop did work again. As a backup, a switch was added to shutdown the drive motor control board so the tracks could always be stopped.

To confirm that taking the relay beyond its rating caused this problem the robot was run from a single LiPo and the relay did not fuse. In this situation the E-stop system and software E-stop operated as in Section 4.4.2.2. Removing the power from the power board does trigger an emergency stop and on start-up the reset button must be pressed (and E-stop button released). With a new relay rated to 120 A (the battery fuse rating) the E-stop functions should reliably meet the specification.

5.1.8.5 Communication

The power distribution board USB communication with the computer proved reliable other than if the board was unpowered and reset without the robot computer restarting since the port on the computer was not correctly closed. Investigation into re-acquiring the power board after a reset should be investigated in robot software.

5.1.8.6 Supply Switching

The robot could be switched between mains and batteries in any order without losing power.

5.1.8.7 Voltage Regulation and Output Switching

The 5, 12, 15 and 18 V supplies were stable during current draw from them. After prolonged testing over tough terrain the 5 V supply repeatedly dropped out for short periods of time causing the router, webcams, and microcontrollers among others to reset. This problem requires further investigation but is likely caused by a dry joint on the PCB that needs fixing. The 5 V supply from the temporary power board was fitted to the rear of the robot to power these crucial devices.

The fuses used on the power distribution board outputs are quickblow. This resulted in fuses blowing if any connectors were removed or connected while the robot was powered. The modular design and easily removable central section made allowed any blown fuses to be rapidly replaced. The output switching was tested with all peripherals attached and functioned correctly.

5.1.8.8 Cooling

The relay did overheat due to exceeding its current rating. A properly rated relay is expected to overcome this problem. The computer did overheat when powered outside the robot for long periods of time. Inside the robot the bottom extraction fans kept the computer cool and no overheating occurred even when running the AI and mapping functions.

5.2.1 Belt Drive Testing

The 2009 drive system is being maintained from the 2008 design although the pulleys are moving location. The wrap angle is being lowered from 180° to 150° although this will not cause a problem as the T10 profile demonstrates sufficient rigidity and depth to prevent slipping in all but the slackest systems.

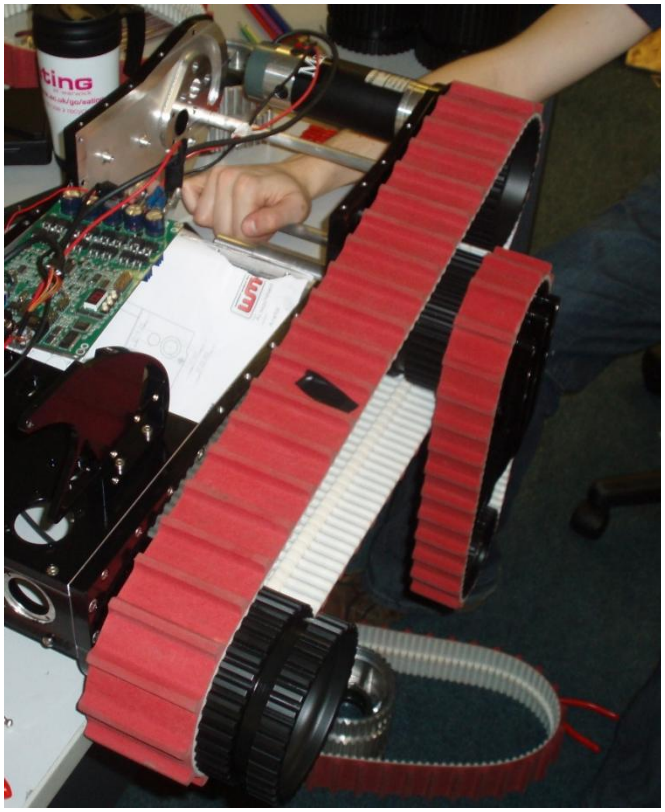


Figure 5-7:Drive belt testing

Once the side plates had been machined a side assembly was produced including drive motors, compound pulleys, one flipper arm and drive pulleys. As shown in Figure 5-7, the assembly was tested using a 24V power supply and the AX3500 control board via a desktop computer.

Initial tests proved successful but later tests developed issues with belts skipping teeth and the motors drawing higher currents intermittently. After close inspection and testing of both belts and pulleys it was observed that one pulley was machined slightly off centre, altering the tooth profile depth by around 1mm and removing the edge chamfer from the tooth profile. This allowed the belt T10 profile to work up the tooth on the pulley once per revolution. Further testing concluded that skipping was only present over wrap angles of over 130°, and so moving from the front to the rear of the compound pulley in question removed the need for re-machining of the component.

Arena testing, no weight running and periods on flat ground have demonstrated that the issue no longer arises.

5.2.2 Flippers

The Maxon motor provided ample power for moving the rear flippers and lifting the robot. The Maxon gearbox produces a slow output rotation but this is preferred as delays in video response across the control network could lead to toppling if movement is faster than that which is observed by the operator. The combination of flippers allows the robot to raise onto all four flipper ends.

5.2.2.1 Chain Drive

The robot was operated for extended periods with load on the flipper arms. It was capable of rising onto the ends of all four flipper arms.

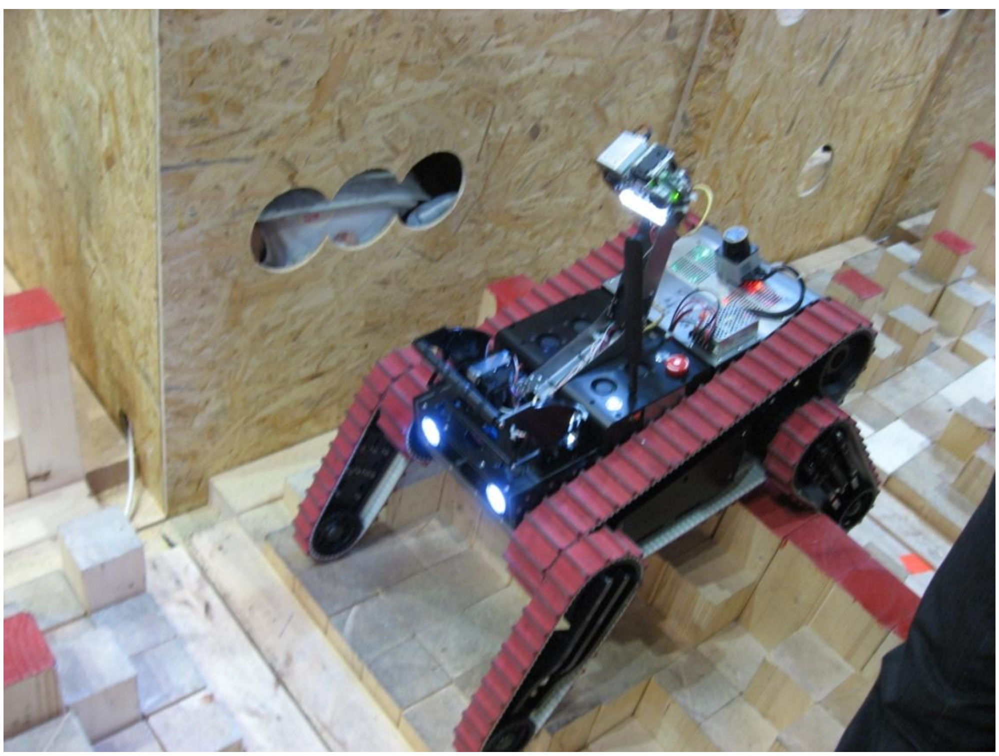


Figure 5-8: Robot on all four flipper arms

5.2.2.2 *Grub Screw Failure*

During first round trials it became apparent that the front flipper set had lost drive. A full strip down of the front end was carried out leading to the discovery of sheared grub screws, Figure 5-9, in the Parvalux sprocket bush.

Figure 5-9: Sheared grub screws from the Parvalux gearbox output shaft

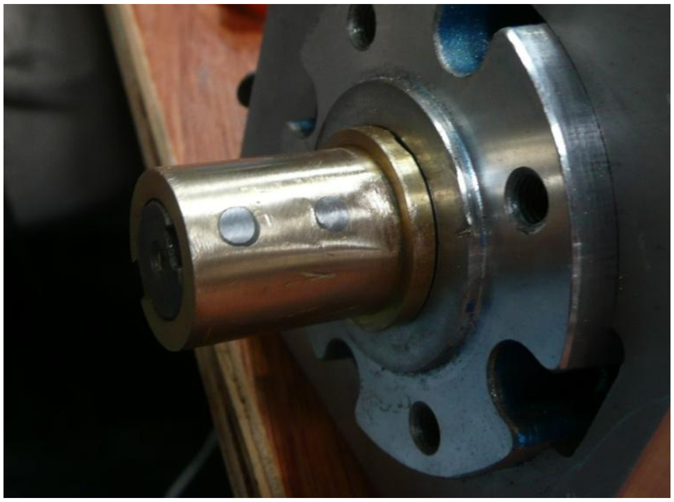


Figure 5-10: Parvalux gearbox output shaft with grub screw replaced

The shear loading on the grub screws had proved too great. Upon investigation the cause was identified; where the grub screws had been shortened from 8mm to 6mm, the 2mm of material had been removed from the lower end in order to retain the socket head for fitting. The shearing occurred across the hollow area of the screw whereas the solid body had been used for design strengths.

In order to return the robot to a running form both flipper motors where removed and the sheared cut grubs replaced with solid bolts and reassembled. Significant periods of high shear across the bolts were present during later testing without failure of the system.

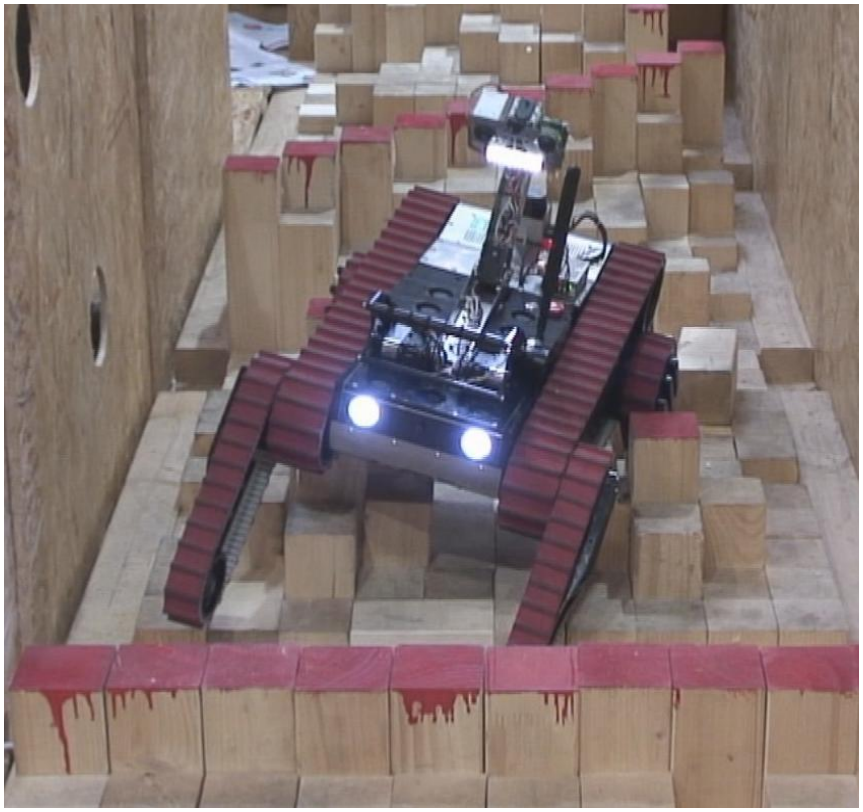


Figure 5-11: Robot negotiating Red Stepfields

5.3 System Integration and testing

Full integration and testing was performed for, and during, the 2009 RoboCup German Open.

5.2.3 Mobility

During terrain trials the robot ascended and descended a 45° ramp and crossed six different red stepfields (asymmetric). It descended a stair case of five steps with rounded corners, however failed to reach the top of the flight. This is thought to be due to weak batteries at this stage of the run and later due to drive motor damage, the extent of which is still unknown.

The robot climbed four of the five steps without tipping indicating that it is mechanically capable of the climb but the power systems need investigation. Stability over stepfields was good and the rear flippers are capable of 360° rotation.

5.2.4 Power Systems

The power system was tested independently and as part of the robot. The power system met its subsystem specification and the robot runs for 30 minutes over terrain and two hours of casual driving. Also, the final robot mass is 43.1 kg which is within the target of no more than 10 kg above the 2008 robot mass at 36 kg.

5.2.5 Victim Identification

The robot can detect form, movement and heat with points being scored at the competition for these signs of life. In addition sound can be detected but was never successfully used during a competitive run. The CO_2 sensor arrived two late due to supplier error and was never implemented. The robot arm allowed the sensors to be best positioned to score points and detect victims.

5.2.6 Tele-Operation

An operator could drive the robot remotely at all points in the arena (30 m across) from the adjacent operating booth. There was some lag caused mainly by the number of other wireless networks in proximity to the arena. Testing in isolation showed much less lag.

5.2.7 Autonomy

Brief autonomous trials were performed using the final robot during the RoboCup competition. On flat surfaces the robot could avoid obstacles spaced less than 1.2 m apart. The slopes in the arena required a design change, moving the LiDAR to the robot rear and angling upwards. Considering the short amount of time to tweak and tune for these tests, they were surprisingly successful with full obstacle avoidance and ability to navigate appropriate sections of the competition course.

Figure 5-12: System testing at RoboCup competition

5.2.8 Mapping

Due to the limited trials of autonomy and poor LiDAR mounting for the sloping floors it was not possible to create a reliable map in competition environment. A map was produced of an AI run outside the arena but due to the moving obstacles (e.g. people) its accuracy could not be evaluated. The mapping algorithm does look promising from simulation.

6 Subsystem Design Discussion

Discussion is from the point of view of the designed subsystems since testing made the actual behaviour of each subsystem clear. This leads to subsystem improvements to better meet the overall robot capabilities (Section 7).

6.1 Chassis

The chassis provides an extremely strong and reliable base for protection and housing of all computer and drive equipment. However, at a total robot weight of 43.1kg it is heavy. A sheet system with a tubular frame and cross bracing system would provide more internal space and help to reduce running weight. Power could also be saved by the reduced weight allowing increased operational time.

Ease of access into the computer compartment and front and rear motor housings from the modular design proved of great importance when attempting to locate and fix issues as they arose.

6.2 Drive System

The tracks produced performed to specification with grip over all surfaces and little wear in the time that the competition was run. An unforeseen problem with the tracks occurred when newspaper and debris was added to the arena. This debris could be picked up between the tracks and the drive pulleys. This occurred in one particular run and produced a jam in the drive system forcing an end to this run.

Possible solutions to this problem include the addition of a skirt around the pulleys and tracks to try and eliminate the possibility of debris and paper stopping the drive system. Another solution would be to develop wheels rather than tracks as the main drive mechanism, much like the Cutlass robot (Remotec). To ensure that this system allows traction over all terrain and the ability to traverse the event arena it would be necessary to increase the size of the robot. This increase in size would produce further problems, however, due to the size limitations of the event arena – it would be necessary to have a wheel base of at least 3 stairs – i.e. 640mm minimum. This would make turning in the arena, both in tele-operated and autonomous modes much more difficult as the arena limitations are only 1.2 m. Therefore in terms of the competition it is unlikely that a solution to this problem will present itself, it should be noted that in the 5 days of competition (of which 3 had debris included in the scenario) the locking of the drive system only occurred once in 6 runs. Therefore it can be assumed that the problem is unlikely to be terminal in the majority of runs in competition, so it is suggested that the current set-up is adequate for the scope of the RoboCup Rescue competition.

With both flipper arms raised a wall protrusion could get between the flipper pulleys meaning that the robot could not move forwards or backwards, or skid turn. One pulley repeatedly collided with the wall. Having a flipper set along the robot side helps reduce the chances of this problem occurring but is a general fault with a skid-steer robot. Similarly, when up against a wall sideways the robot cannot turn away from the wall.

6.3 Stability

When the robot rolled into a position where robot weight was primarily on one flipper arm in a transverse direction, the flipper could twist and bend. The nylon flipper arms are flexible and no damage occurred but the tracks do lift off the pulley giving and although this could produce a situation with no traction, immobilising the robot, this did not occur in competition. Moving the flippers in this situation could also cause permanent flipper damage or catastrophic failure, further investigation into transverse loading of flipper arms should be performed.

6.4 Power

The switching circuitry worked well but replacement of the emergency stop relay is needed. Also, the power distribution PCB could be redesigned to provide better air flow to the lower parts of the central section and with more thought to wiring.

6.5 Central Computer

The computer case was designed to utilise the whole volume of the central section of the chassis whilst still allowing adequate airflow and keeping component temperatures at acceptable levels. The airflow did maintain temperatures levels for the processor and other electronic components low enough to stop any failures due to overheating. However, due to the tight fit of the central section the ease with which the whole subsystem could be removed from the central chassis was slightly worse than expected, though it was possible to remove and replace the casing quickly between competition runs. The difficulty was increased due to the number of wires and connections present in the subsystem. Therefore to produce a computer case which is fully to specification in that it can be easily removed one must allow more space between the casing and the central chassis, it would also be preferable to allow more airflow from the top to the bottom of this section, perhaps through production of a slightly smaller power control board. It should be noted here that the processor temperature did not reach the critical level of 60^{o}C at any stage throughout the competition even with possible restricted airflow.

6.6 Victim Identification

6.6.1 Tele-operated

Victim ID was made through heat signature, form of victim and state. Identification of hazard labels and tumbling Es was also possible when the head was well aligned with the opening to entombed victims. The remaining sense to be developed is CO_2. This would complete the range of senses accessible for the tele-operated region.

6.6.2 Automated

The blob detection algorithm does return the location of blobs in the thermal camera's field of view. Full integration and testing with the robot AI still needs to take place.

6.7 Robot Arm

The robot arm significantly aided the driving by being able to direct the cameras to see flippers and over edges. It could also be moved in close to victims to read tags and score full points. However, although the servos used in the arm are overrated for normal use, they can be taking beyond their rating in unusual circumstances. All three RX64 servos were damaged when the arm was driven to a position that pushed the lower arm into the lid and when the robot rolled towards a wall. The servo built in torque and temperature protection appeared to fail. Angle limits on the servos could avoid these damaging situations. Alternative servos or a radical arm redesign should be investigated. Possible directions include linear actuators similar to those on the robot by the Upper Austria University of Applied Sciences(14) or reducing the arm capabilities and using a wide angle camera with directional zoom.

6.8 Mapping

Testing was performed with the AI and mapping is an important part of the competition and score many more points per victim. In simulation the mapping was promising and full testing with a static environment using real LiDAR data is required.

6.9 Communication

The competition demands the use of the IEEE 802.11a standard. This is becoming an obsolete network standard so finding hardware is difficult. Frequent slow connections were found in the wireless network, not helped by the numerous other networks at the competition. Better connections could be observed using a wireless access point on the robot and wireless computer adapter made by the same company. Radio control could also be investigated for the drive motors to give responsive control and freeing up network bandwidth for sensor data to improve camera lag.

To evaluate the effects of using wireless networks, the robot was connected over Ethernet. With this faster, high-bandwidth connection the camera lag was reduced. This suggested that the wireless network was a bottleneck. Using wireless network analysis software ("sniffer software") a free channel could be selected to give much lower lag.

6.10 Navigation

6.10.1 Tele-operation

The tele-operation interface was well optimised to provide a range of feedback to the controller. Feedback data includes:

- Front and rear webcams
- LiDAR data
- Thermal imaging
- Microphone
- Flipper position

The data here allowed a good level of control awareness from the operator station although several issues with the client, server and wireless caused poor communication.

Large lag delays on the webcams made control difficult and further complications occurred when commands overran causing the robot to spin on the spot.

6.10.2 Autonomous Operation

Limited AI trials were performed and these were outside of competition. The addition of the radio dropout zone (an area where communication fails and the robot must navigate to a point where it can pick it back up) provides a good opportunity for WMR to attempt autonomy and closely matches the motivation for autonomy a single rescue robot that will always have an operator. Consideration must be given to the LiDAR mounting so that the AI can handle 10° slopes and the slopes should be modelled when simulating to properly tune the AI.

6.11 Manipulation

No manipulation existed although there was the suggestion of adding a bar system at the front of the head to allow basic manipulation. This was not attempted due to time restraints. The arm is on the smaller end of being able to reach and manipulate objects and as such during the arm redesign a considerable reach increase and payload limit are considered necessary.

The blue pick-and-place arena at the competition is now a permanent feature and manipulation is a good development area since it was not attempted by any teams at the German Open. It would be an impressive feature and could encourage development by other teams of an important aspect of a search hand rescue robot.

6.12 Simulator

Due to the short timescale of the project, initial testing on the final system was not possible until the RoboCup competition. Early runs where delayed as software and mechanical systems were combined and asked to perform and issues were identified and remedied as they became apparent. The simulator provided a good base for software development while the robot was out-of-action and should be continued, ideally linking in the other robot sensors.

6.13 Failure Modes

A Failure Modes and Effect Analysis is provided in Appendix D for the final robot.

7 Further Work

Roadmaps were produced to direct the 2009 development and also outline suggested work for the next two years.

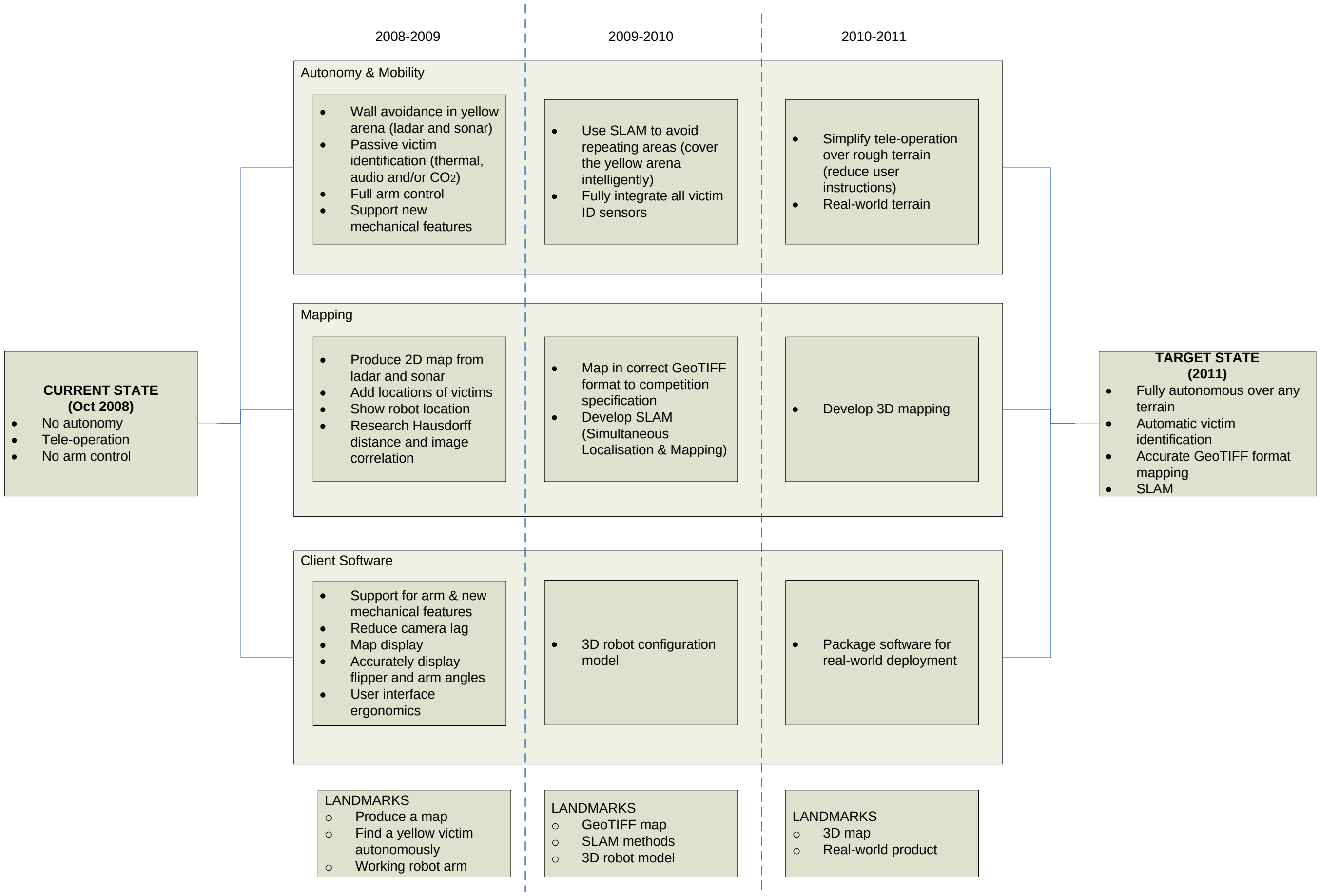


Figure 7-1: Electronic and Software Development Flow

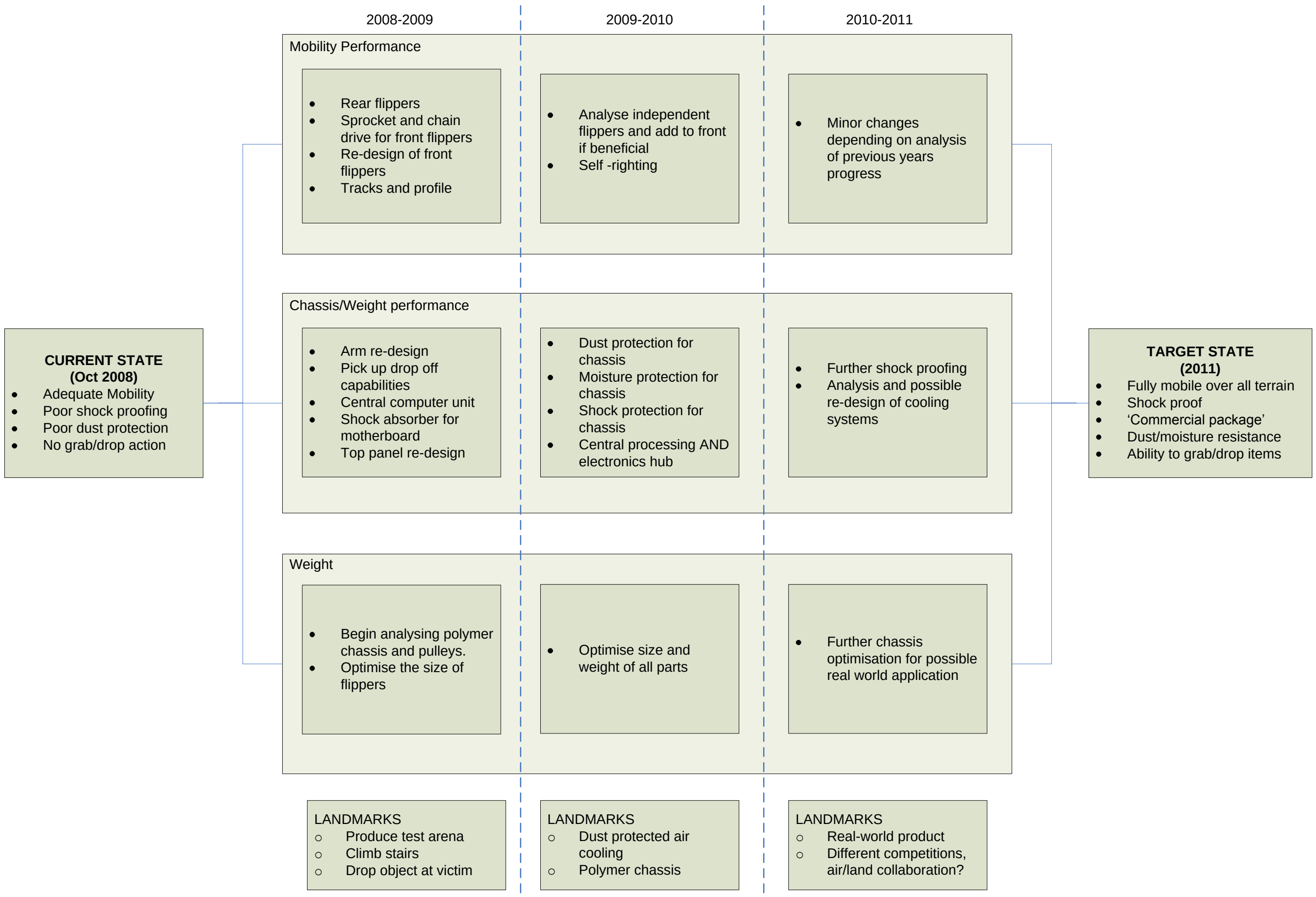


Figure 7-2: Mechanical Development Flow

7.1 Chassis

The design of the chassis and the level of mobility demonstrated is at a high level. Therefore it is recommended that the chassis design be maintained, at least in design and function. Analysis of weight saving options should be of high importance to reduce power demand during operation.

Panel thinning could be used to provide extra space in the chassis for connectors and cable managements making assembly and maintenance easier than currently observed.

7.2 Drive System

Introduction of tensioning pulleys rather than tensioning the chassis to simplify the chassis side design and provide easy adjustment to each side if differential stretching of belts occurs.

Look into drive motors to ensure they are not under rated for prolonged large obstacle driving. Some analysis of drive motor power specification is provided in Section 0

Solve the problem of debris entering the pulley and belt system and locking up drive. Look at the viability of a seal system for the running gear.

7.3 Stability

Providing a key and keyway for the collar of the flipper motors – eliminating the need for grub screws, or bolts to be used to fix these collars – proved to be a weak point.

Change the front flipper motor to a smaller, lighter motor, again reducing weight and providing full 360^{o} rotation.

7.4 Power

The current drive motors are underrated for the mass of the robot particularly when ascending ramps and stairs. New motors should be specified and are recommended to be in the power range of 250W continuous, this is based on the following calculation:

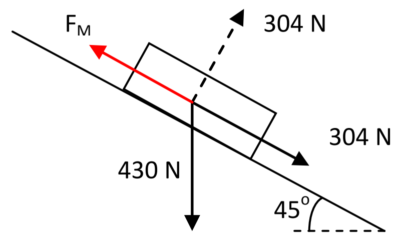


Figure 7-3: Force diagram of robot on a ramp

Given the force down the slope of 304 N the motor must apply a force at the edge of the pulley of greater than this 304 N.

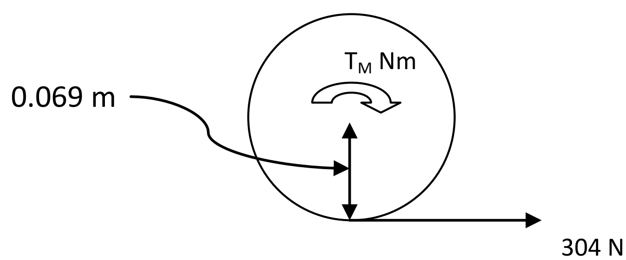


Figure 7-4: Force diagram of pulley

The torque applied at the pulley:

$$T_M = 304 \times 0.069 = 21 \text{ Nm}$$

Assume robot speed up ramp is 0.5 ms^{-1}, therefore the speed of the pulley must be:

$$\omega = \frac{V}{r} = \frac{0.5}{0.069} = 7.25 \text{ ms}^{-1}$$

Thus the required motor power is:

$$P = T\omega = 21 \times 7.25 = 152 \text{ W}$$

The batteries characteristics cause them to drop voltage rapidly as their stored charge reaches a low level. Little sign of power loss is reached until this rapid drop stage. A voltage monitoring system should be incorporated to protect hardware and control systems.

Quickblow fuses are vulnerable to hot plugging and slow blow fuses would be more appropriate.

7.5 Central Computer

The central computer case allowed for sub-system testing of the computer stack and also extraction of the casing from the central section. However, as discussed there remain a number of areas that could be developed further. The first of these is to place removable access panels into the acetal lid and the side panels of the central section chassis. These would allow easier access to the computer stack to move wires and diagnose problems as they arise.

There is space available on the power control board to produce a more compact design, this would develop more airflow in the central section and also slightly simpler extraction of the computer stack.

Due to the quick assembly of the computer casing, the wiring was not fully considered. This has developed problems when moving the computer case and more care and consideration to the connectors used would provide a much more practical final solution.

7.6 Victim Identification

Current sensors on the arm provide a high level of identification. A CO_2 sensor would be of benefit and is available but needs configuring into the software system. Once completed and mounted on a suitable manipulation platform the robot will demonstrate an extremely competitive level of victim ID.

7.7 Robot Arm

Whilst the current arm provides a reasonable level of performance in terms of movement and direction for the sensors, it is not yet fully capable. Size and payload capacity are the two key issues which need addressing. The farthest obstacles which could be required are over a metre tall and the same in reach. It is not likely that this is achievable but development to reach closer objects at similar heights is an important step forwards in terms of real world usability. Servo motors are not felt to be the strongest solution to the manipulator / sensor bed solution and a more robust worm and spur gear arrangement may prove beneficial.

An adjustable base joint would allow for easier observation of the victims and lower the need for precise locating of the robot chassis relative to the entombed victim which can be challenging on orange and red graded obstacles

Arm control kinematics need to be limited to ensure dead zones protect the motors and gearboxes from self interaction. The current control method of head flight should be maintained for ease of use during tele-operation although the control pad system should be examined as it is not particularly operator friendly.

It was found during the competition that preset arm positions allowed easy access to the most common positions and this system should be developed for any new design.

7.8 Mapping

The map that the current mapping algorithm produces has a tendency to breakdown if a few scans are overlain incorrectly. This can be solved either by developing a more robust correlation technique or by filtering scans of which do not align with the map properly.

Also, the current algorithm only functions in two dimensions, ideally the robot should be mapping in three dimensions to more accurately depict the arena. Pan-tilt with the LiDAR unit is a possible approach.

7.9 Communication

Currently all the sensory data apart from webcams are sent through the same socket (analogous to a pipeline where data flows sequentially), ideally each sensor should have its own dedicated socket connection to allow parallel streaming of data and to reduce communication lag.

The robot should also respond positively to drop-outs of the wireless connection, since the current client needs to be restarted if such an event occurs. This would provide true radio dropout capabilities.

The possibility of radio control for the motors could be investigated to get more responsive control and reduce the amount of data going through the wireless network.

7.10 Navigation

7.10.1 Tele-Operation

Lag reduction must be completed in order to allow faster movement around the arena and more precise adjustment of position whilst manoeuvring over complex obstacles. It is recommended that a Radio Frequency (RF) system be integrated for control of the robot allowing sensor data to be sent over a less crowded network. It is felt this will reduce control lag notably. Care should be taken in any further development of the java code to ensure that information sent over the network is compressed suitably and sent as efficiently as possible to minimise data traffic over the network.

7.10.2 Autonomous Operation

The top performing autonomous robots were designed purely for that aspect of competition. Due to the short duration of missions, it is difficult to attempt both autonomy and go for high mobility obstacles. To obtain the highest scores, victims in both areas should be located. This can be done with two robots with one robot operating autonomously while the other ventures into the other arena areas. WMR could implement this strategy using the unused parts from the 2008 robot and producing the necessary extra parts. Space should be given to this robot for sensor expansion, and should feature pan-tile LiDAR mounting to tackle sloping floors and any future competition developments.

The main robot should be developed for the radio dropout zone which requires an elevated or tilting LiDAR for slopes.

7.11 Manipulation

A manipulator system should be developed to allow for pick and place tasks to be completed. It may be considered appropriate for a simple hook system to be developed over the next year with further work required for a gripper system capable of picking up blocks of 100mm width, height and depth. Of importance is that whatever arm system is developed in future has a load bearing capacity sufficient to allow a manipulator to be housed. It was noted in the competition that pick up and drop off of objects to victims is highly desirable.

7.12 Simulator

The simulator at the moment only emulates a LiDAR and future development should include the addition of sonar, encoders and simulated blobs from the Victim ID algorithm. This allows the robot software to be fully tested while any hardware changes are ongoing.

Noise should also be added to the sensor data to more accurately depict the real world, as no sensor is perfect.

Better logging and debugging facilities should also be developed.

7.13 Demonstration Arena

WMG has asked Warwick Mobile Robotics to produce a full-scale, permanent installation rescue arena in the International Digital Laboratory. This will be used for demonstrations and robot testing. Ensuring that the robot is assembled on ahead of the German Open would guarantee testing time to give the operator ample chance to understand the robot's capabilities and iron out any bugs. This will allow all competitive runs to be maximised for both tele-operation and autonomy.

8 Conclusion

The robot competed in the German Open RoboCup competition where many of the requirements were met.

During the project period the profile of WMR was raised through a series of open days and industrial visits. A long term sponsorship deal has been struck with a main sponsor and WMR and the University of Warwick have now been acknowledged in a new and upcoming international field of research.

Many aims of the project were met although one unfortunate shortcoming was the lack of mapping available during the competition. Despite the short time scale limiting the testing of AI systems an initial trial run proved promising although further work is needed to implement the system into the competition format. A development route to create a competitive lead would be the construction of an autonomous robot which could run alongside the main machine during runs to allow for effective time management of our runs.

Of the two objectives set at the start of the project, both were met during the competition where the robot completed a run over a series of six red step fields proving the design concept and rear flipper arrangement is suitable for the course terrain. This led to WMR receiving the Best in Class mobility award and an invitation to attend the world final in Graz, Austria.

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